Lunar Landing Research Vehicle

ESTIMATED HANDLING QUALITIES

REPORT NO. 7161-954004

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MANUFACTURED

BY

BELL AEROSYSTEMS COMPANY
DIVISION OF BELL AEROSPACE CORPORATION – A TEXTRON COMPANY

FOR NATIONAL AERONAUTIC AND SPACE ADMINISTRATION
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SUMMARY

This report presents the estimated handling qualities of the Lunar Landing Research Vehicle Model 7161. Results presented in this report will be supplemented by a detailed simulation of the vehicle that is being planned by NASA. It is expected that the data presented herein will provide a guide for that work and the initial planning of the subsequent flight test program.

The report is divided into three parts giving, respectively: (1) a description of the LLRV physical characteristics and control systems, (2) detailed description of the piloted analog simulator study conducted by Bell Aerosystems Company and, (3) the estimated handling qualities, flight boundaries, and emergency recovery techniques for the LLRV.

The configuration studied in the Bell simulator program had different aerodynamic characteristics from the present LLRV so, to some extent, the following results give a qualitative indication of the characteristics of the final LLRV configuration.

Satisfactory Handling qualities were exhibited in the attitude position command mode but not in the acceleration command mode. In the rate command mode the vehicle is flyable with pitch and roll control powers greater than about 0.2 rad/sec^2. These results were obtained with attitude rocket on-off threshold less than five percent stick travel when full stick corresponded to up to 2.5 rad/sec in the lunar simulation mode and 1.25 rad/sec in the engine centered mode.

Control power level did not greatly affect the pilot rating except at the low levels (0.2 rad/sec) where the rating deteriorated.

Reducing the attitude rocket-on-off threshold from five percent stick travel to two percent gave a marked improvement in rating (usually greater than one point).

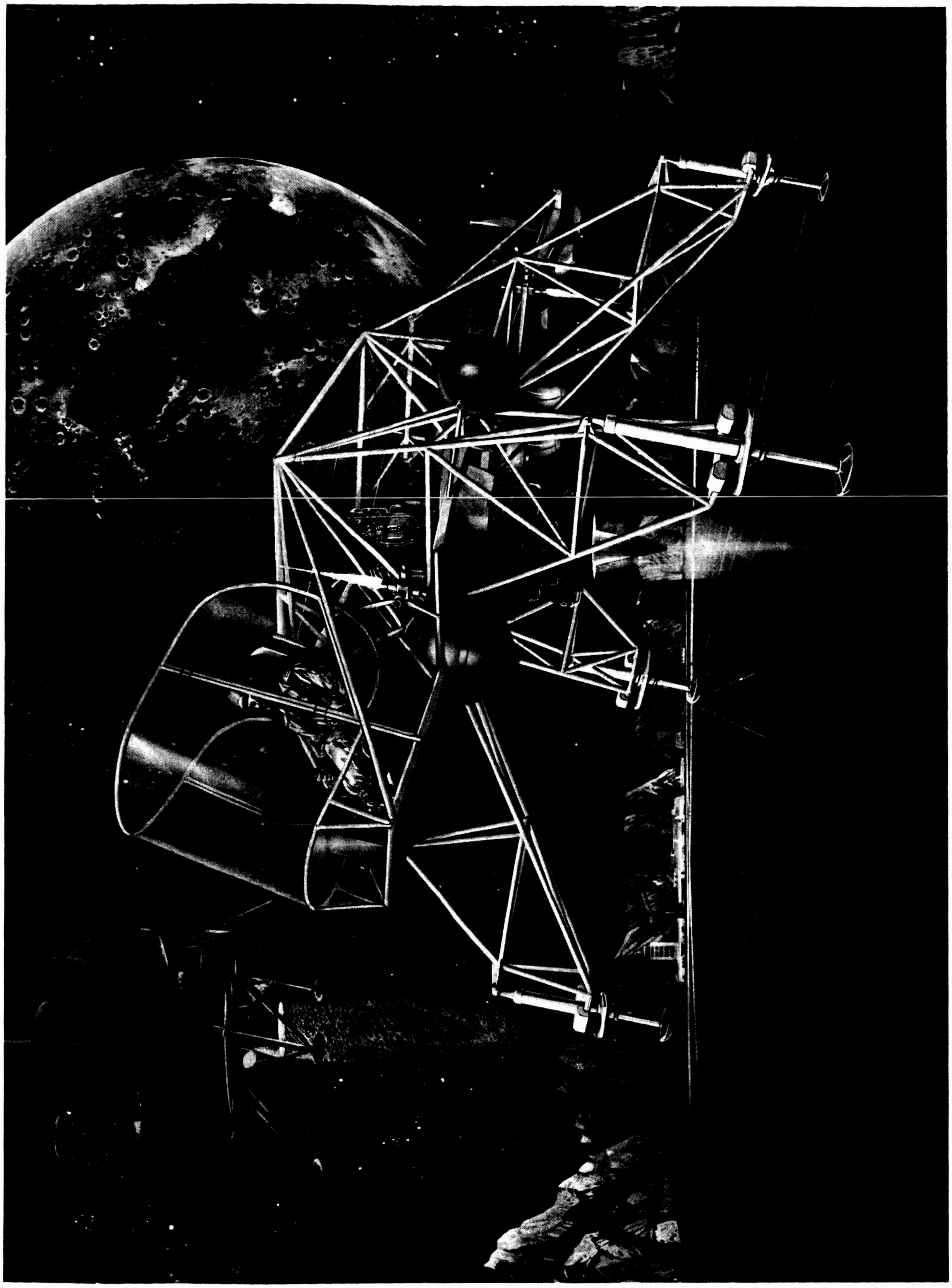
A lower stick sensitivity (i.e., angular rate per inch of stick travel) was required for the engine centered mode than for the lunar simulation mode. The optimum being a stick sensitivity of 0.66 rad/sec and 1.0 rad/sec, respectively, for full stick travel.

Height control was rated by the pilots at values of five to six (unsatisfactory - unacceptable). A main criticism was the opposite senses of the jet engine throttle and the

lift rocket lever actions when switching from the engine centered mode to the lunar simulation mode of flight.

Attitude rocket fuel consumption rates varied from pilot to pilot but showed a close correlation with the ease or difficulty of control. The range likely to be achieved by a trained pilot is from about 11 to 17 pounds per minute.

Recovery procedure in the event of a jet engine failure was investigated. Attitude was easily controlled but altitude and altitude rate were difficult to control within safe limits. Further consideration of the recovery profile has led to a simplification in recovery procedure which should be acceptable to the pilots.



Lunar Landing Research Vehicle

SECTION I

INTRODUCTION

1.1. GENERAL.

The purpose of this report is to give a functional description of the vehicle and control systems and present the information obtained by Bell Aerosystems Company on the handling characteristics of the Lunar Landing Research Vehicle (Figure 1-1), (LLRV). This report, although preliminary in nature, should be of assistance in choosing the significant areas for further investigation and also for the initial planning of the flight test program.

The report encompasses three main sections:

(1) Description of the LLRV. - This section describes the present vehicle and its method of operation. A summary of the physical characteristics, aerodynamic forces and moments, and a detailed discussion of the altitude control system and its operation is given.

(2) Piloted Analog Simulator Study. - This section presents a detailed description of the simulator study carried out by Bell Aerosystems Company and is the basis of the estimated handling qualities.

(3) Estimated Handling Qualities. - The results of the simulator study are discussed and interpretations for the flying characteristics of the LLRV are made. The main areas covered are attitude control, height control, fuel consumption rates, and emergency recovery procedures.

1.2. LIST OF SYMBOLS.

A_{e_x}, A_{e_y}, A_{e_z}	Components of aerodynamic force on engine in vehicle x, y, z directions.
A_{v_x}, A_{v_y}, A_{v_z}	Components of aerodynamic force on outer frame in vehicle x, y, z directions.
g	Acceleration due to gravity (32.2 ft/sec^2).
g_x, g_y, g_z	Components of acceleration due to gravity in vehicle x, y, z directions.
K_ϕ, K_θ, K_ψ	Attitude position gyro feedback gains for roll, pitch and yaw.
K_p, K_q, K_r	Attitude rate gyro feedback gains for roll, pitch and yaw, (See Figure 2-5).
L	Vehicle characteristic length = 7.0 ft

L_{D_e}, M_{D_e}, N_{D_e}	Roll, pitch, yaw moments due to aerodynamic drag on engine.
L_{D_v}, M_{D_v}, N_{D_v}	Roll, pitch, yaw moments due to aerodynamic drag on vehicle (outer frame).
L_p, M_q, N_r	Roll, pitch, yaw moments on vehicle due to rotation of vehicle (outer frame).
L_A, M_A, N_A	Roll, pitch, yaw moments on vehicle due to attitude control rockets.
p, q, r	Rate of roll, pitch, and yaw about vehicle x, y, z axes.
S	Vehicle reference area = 38.48 ft^2
T_{j_x}, T_{j_y}, T_{j_z}	Components of jet engine thrust in vehicle x, y, z directions.
T_{R_L}	Lift rocket thrust (Vehicle z direction only).
u, v, w	x, y, z Components of velocity
u_w^2	$u^2 + v^2$
V_o^2	$u^2 + v^2 + w^2 = u_w^2 + w^2$
x, y, z	Distances along the positive x, y, z directions (see Figure 2-3).
ρ	Density of air slugs/ft^3
ψ, θ, ϕ	Euler transformation angles from earth axes to vehicle body axes, yaw, pitch and roll, respectively.

SECTION II

DESCRIPTION OF LLRV

2.1. GENERAL.

The Lunar Landing Research Vehicle is illustrated in Figure 1-1 and the general arrangement drawing, Figure 2-1. It consists of a four-legged truss framework supporting a pilot's compartment at the front and an instrumentation package at the rear. A jet engine is suspended between the legs with its thrust axis vertical. The engine is mounted on a gimbal which allows the thrust axis to be tilted in pitch and roll relative to the vehicle outer frame.

There are two basic modes of flight:

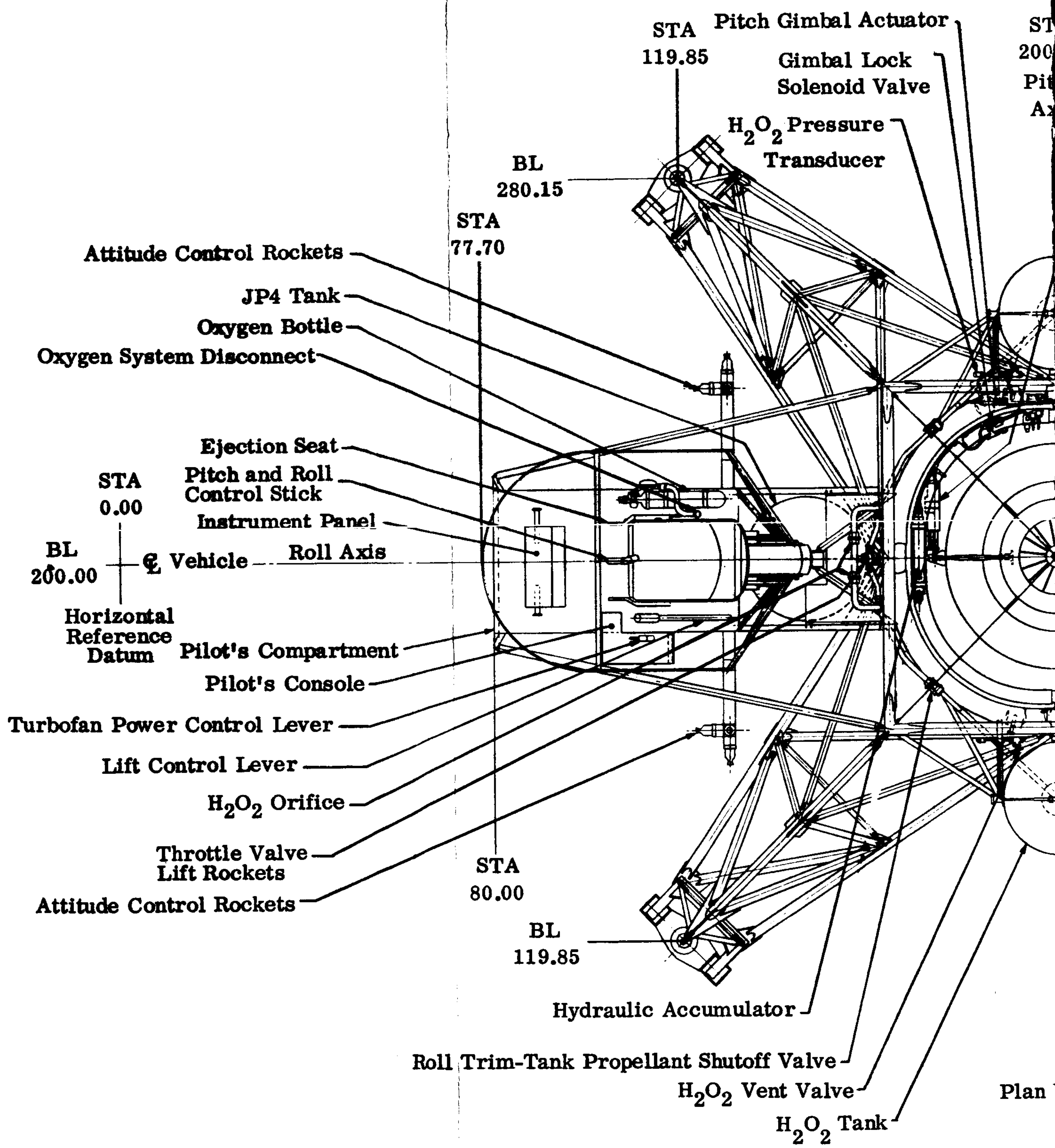
(1) Lunar Simulation Mode and

(2) Earth Mode.

2.1.1. Lunar Simulation Mode. - When in the lunar simulation mode, the jet engine thrust vector is automatically controlled in magnitude and direction to provide a vertical lift equal to 5/6 of the vehicle instantaneous weight and to overcome aerodynamic drag. The remaining 1/6 of the LLRV weight is supported by two throttleable lift rockets, controlled by the pilot and having a maximum thrust of 500 pounds each. The resultant thrust vector of the lift rockets is permanently aligned with the vehicle (outer frame) z-axis so that a rotation of the vehicle from a vertical position causes horizontal translation.

2.1.2. Earth Mode. - To conserve rocket engine fuel, the vehicle is flown to the altitude chosen to start the lunar simulation in the earth (or engine centered) mode. In this mode, the jet engine is held fixed relative to the outer frame so that the thrust axis is aligned with the vehicle (outer frame) z-axis. The pilot controls the jet engine thrust to support the entire vehicle weight.

2.1.3. Attitude Control. - Attitude control is achieved with 16 smaller (90 pounds maximum thrust) rockets arranged so that eight provide pitch and roll control and eight provide yaw control. These rockets can be ground adjusted to give thrust levels down to 18 pounds each. They are controlled in flight by on-off (not proportional) valves.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119.85
Pitch Gimbal Actuator
Gimbal Lock
Solenoid Valve
H_2O_2 Pressure
Transducer
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Attitude Control Rockets
JP4 Tank
Oxygen Bottle
Oxygen System Disconnect
Ejection Seat
Pitch and Roll
Control Stick
Instrument Panel
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Datum
Pilot's Compartment
Pilot's Console
Turbofan Power Control Lever
Lift Control Lever
H_2O_2 Orifice
Throttle Valve
Lift Rockets
Attitude Control Rockets
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BL
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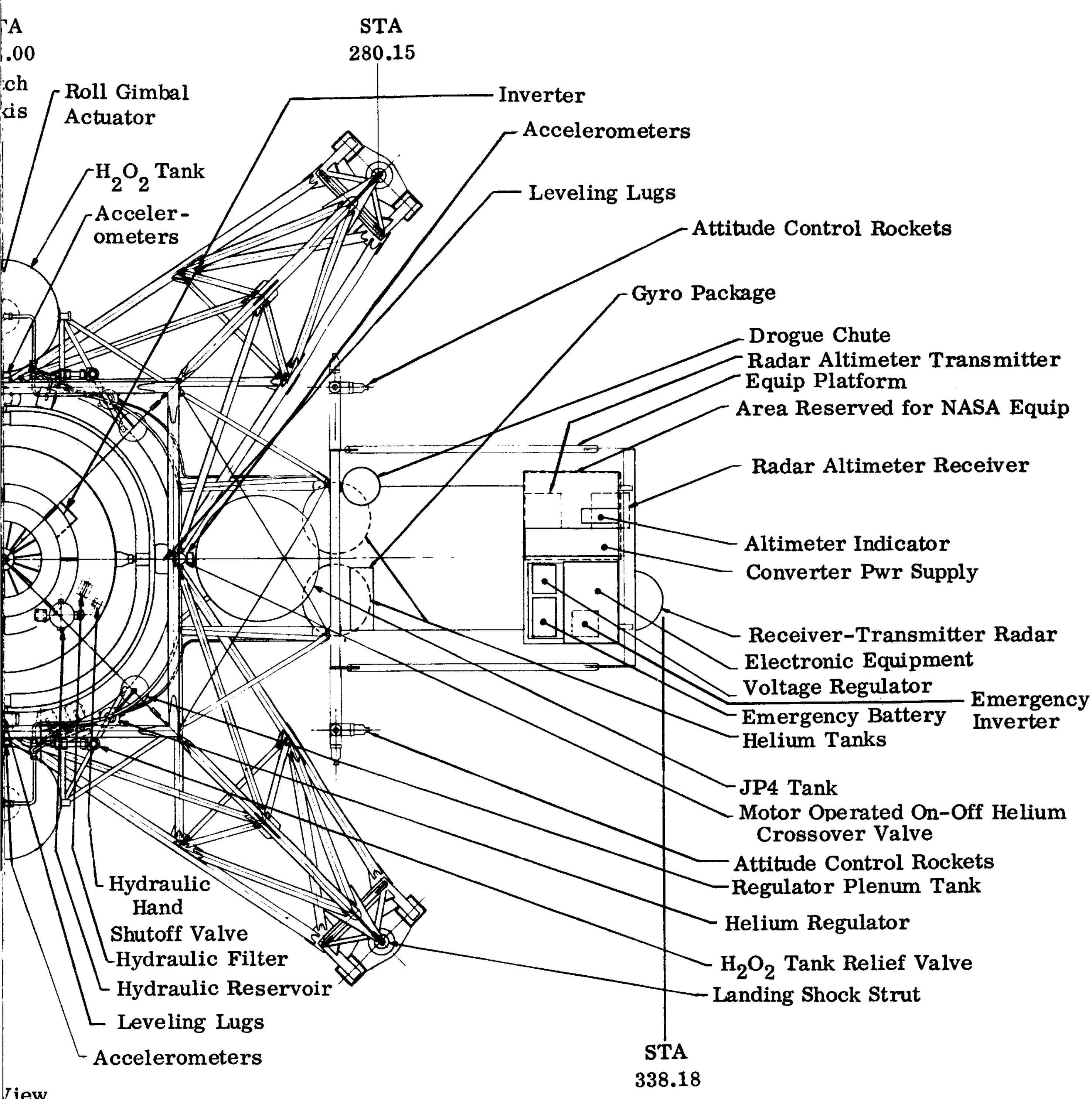
Hydraulic Accumulator
Roll Trim-Tank Propellant Shutoff Valve
H_2O_2 Vent Valve
H_2O_2 Tank



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H_2O_2 Tank
Acceler-ometers
Inverter
Accelerometers
Leveling Lugs
Attitude Control Rockets
Gyro Package
Drogue Chute
Radar Altimeter Transmitter
Equip Platform
Area Reserved for NASA Equip
Radar Altimeter Receiver
Altimeter Indicator
Converter Pwr Supply
Receiver-Transmitter Radar
Electronic Equipment
Voltage Regulator
Emergency Inverter
Emergency Battery
Helium Tanks
JP4 Tank
Motor Operated On-Off Helium Crossover Valve
Attitude Control Rockets
Regulator Plenum Tank
Helium Regulator
H_2O_2 Tank Relief Valve
Landing Shock Strut
Hydraulic Hand Shutoff Valve
Hydraulic Filter
Hydraulic Reservoir
Leveling Lugs
Accelerometers
STA
338.18
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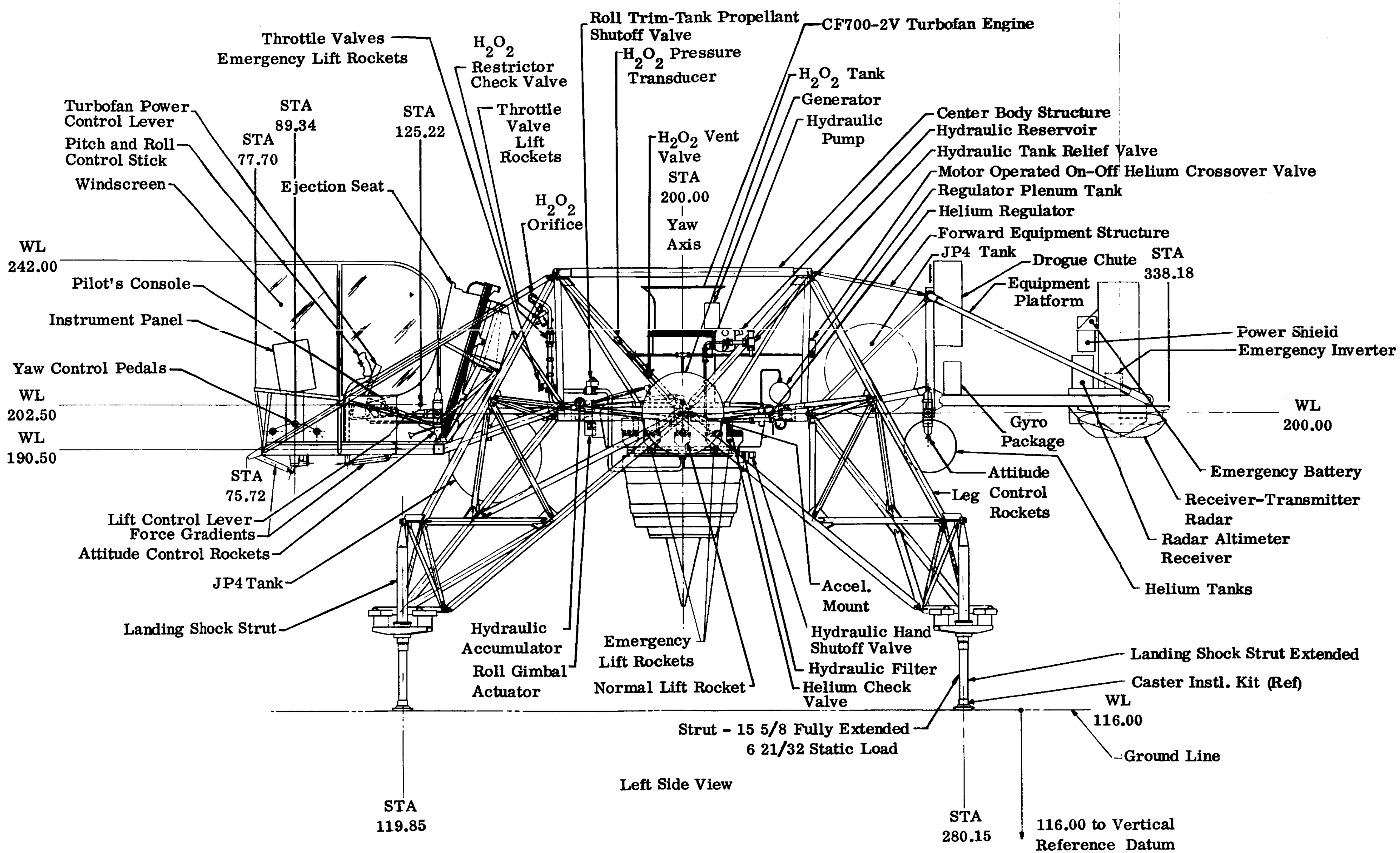


Figure 2-1. LLRV General Arrangement

2.2. PHYSICAL CHARACTERISTICS.

Data given in this section is for reference only. Consult the appropriate handbook for exact data.

Weight. -

Vehicle Outer frame including 200 lb pilot			1796 lb
Engine gimbal mounted			870 lb
Fuel:	JP4	Jet engine	400 lb
	H_2O_2	Lift rocket	500 lb
	H_2O_2	Attitude rocket	100 lb
Gross Weight			3666 lb

Inertia. - See Figure 2-2.

Turbofan Jet Engine. -

CF-700-2V ducted fan (contra-rotating)	
Maximum thrust (standard day sea level)	4200 lb
Specific fuel consumption	0.7 lb/hr/lb

Lift Rockets. -

Maximum thrust (pilot throttleable)	500 lb/rocket
Specific impulse	122 lb sec/lb

Attitude Rockets. -

Thrust range (ground adjusted)	18 to 90 lb
Specific Impulse	100 lb sec/lb

Attitude Control Power Range. - See Figure 2-2.

2.3. ATTITUDE CONTROL SYSTEMS.

Pitch and roll control is accomplished by means of four pairs of rockets: each pair providing an upward directed thrust and a downward directed thrust. Yaw control is provided by an additional four pairs of rockets thrusting sideways and fore or aft. The arrangement is as shown on Figure 2-3. Three firing arrangements, or modes; are possible: these are termed BOTH, STANDARD, and TEST.

200 LB PILOT		ENGINE CENTERED MODE FULL FUEL	ENGINE CENTERED MODE EMPTY	LUNAR SIMULATION MODE FULL FUEL	LUNAR SIMULATION MODE EMPTY
Weight – lb		3666	2666	3666	2666
I_{xx} – slugs ft^2		1100	776	1040	716
I_{yy}		2800	2535	2737	2472
I_{zz}		3318	2742	3318	2742

Maximum control moments: Roll 1080 lb ft
Pitch 2100
Yaw 1590

		FULL FUEL	EMPTY	FULL FUEL	EMPTY
Max. Control Power Rad/Sec^2	Roll	0.9818	1.391	1.038	1.507
	Pitch	0.75	0.828	0.767	0.849
	Yaw	0.479	0.58	0.479	0.58

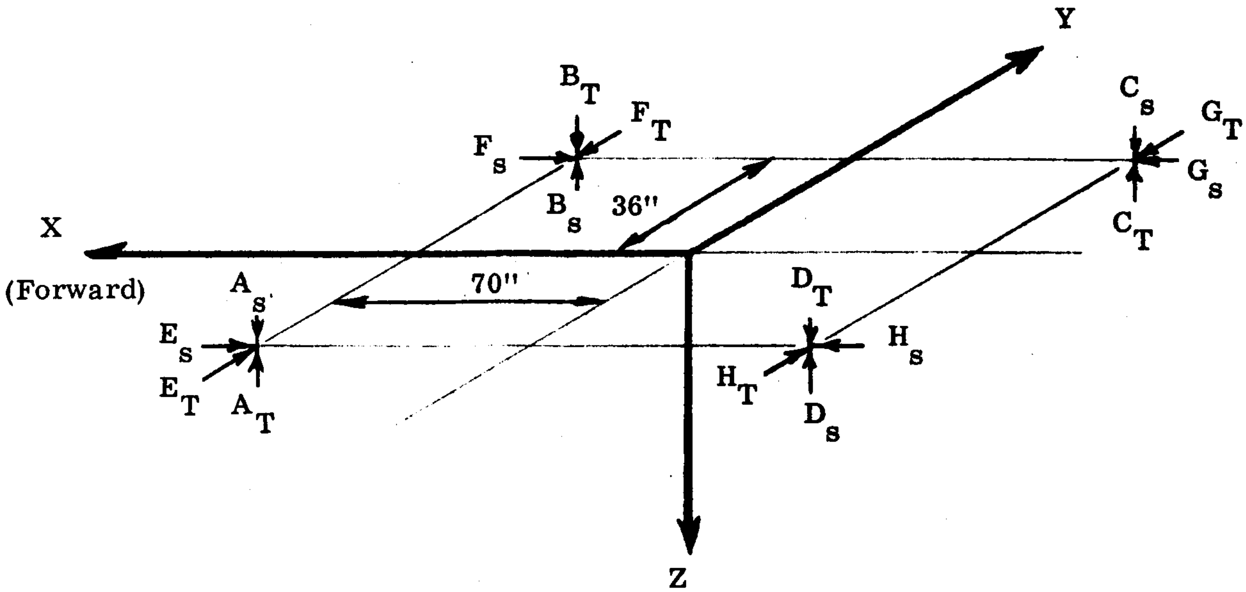
150 LB PILOT		FULL FUEL	EMPTY	FULL FUEL	EMPTY
Weight – lb		3616	2616	3616	2616
I_{xx}		1115	780	1055	720
I_{yy}		2510	2250	2447	2187
I_{zz}		2925	2351	2925	2351
Max. Control Power Rad/Sec^2	Roll	0.969	1.384	1.0233	1.499
	Pitch	0.837	0.933	0.858	0.96
	Yaw	0.544	0.676	0.544	0.676

Minimum Control Powers:

Pitch and Roll: $\text{Minimum} = \dfrac{\text{Maximum}}{10}$

Yaw: $\text{Minimum} = \dfrac{\text{Maximum}}{10}$

Figure 2-2. LLRV Control Powers



Rocket		A_S	A_T	B_S	B_T	C_S	C_T	D_S	D_T	E_S	E_T	F_S	F_T	G_S	G_T	H_S	H_T
Pitch	Up		✓	✓		✓			✓								
	Down	✓			✓		✓	✓									
Roll	Right		✓		✓	✓		✓									
	Left	✓		✓			✓		✓								
Yaw	Right										✓	✓			✓	✓	
	Left									✓			✓	✓			✓
Pitch Up and Roll Right (Both)			✓			✓											
Pitch Up and Roll Right (Test)			✓														

For Both : Rocket with subscripts S and T fire
Standard : Rocket with subscript S fire
Test : Rocket with subscript T fire

Figure 2-3. Attitude Control Rocket Layout and Firing Sequence

2.3.1. Both Mode. - This mode uses all the rockets and the firing logic as shown in Figure 2-3. It will be noted that, when pitch and roll are commanded simultaneously, there are two pairs of rockets on which both the upward and downward nozzles could be scheduled to fire, and thus cancelling each other and halving the nominal control power. To eliminate the fuel wastage that would result, the firing circuitry prevents opposing rockets from firing.

2.3.2. Standard Mode. - This mode uses only eight of the sixteen rockets. Their thrust is set prior to flight at a standard level (90 pounds) which is known to provide adequate control. The firing logic is indicated by subscript "S" on Figure 2-3. As with Both, when demanding pitch and roll simultaneously, there are rockets which could be thrusting in opposition thus halving the nominal control power. However, these conflicting rockets are cut out. This means that only one rocket is firing and it results in a small translation force as well as a moment.

2.3.3. Test Mode. - This mode is similar to the Standard mode except that the other eight rockets (subscript "T") are being used. Thrust level is set at any desired test level from 18 to 90 pounds.

The pilot has the ability to change from Test to Standard or Both at will by using a switch on the pilot's console. All the rockets can be ground adjusted to give a thrust level in the range of 18 to 90 pounds. This adjustment, together with being able to use half the rockets (either the TEST or STD set or BOTH) provides the capability to vary control power by a factor of 10.

2.3.4. Firing Control. - Control of the rockets is such that they are either on or off; they are not proportional type. The threshold is achieved as shown on Figures 2-4 and 2-5.

Both the threshold which the pilot has to exceed before the rockets fire and the value below which they cease to fire can be ground adjusted. It should be noted that the rocket firing circuit logic results in an equivalent stick threshold at 45 degrees to the pitch and roll axes. (See Figure 2-4).

By incorporating vehicle attitude rate and position feedback signals into the control loop, three modes of attitude control are possible. The pilot can command an attitude position, a rate of change of attitude, or an attitude acceleration. A diagrammatic representation of these three systems is shown on Figure 2-5.

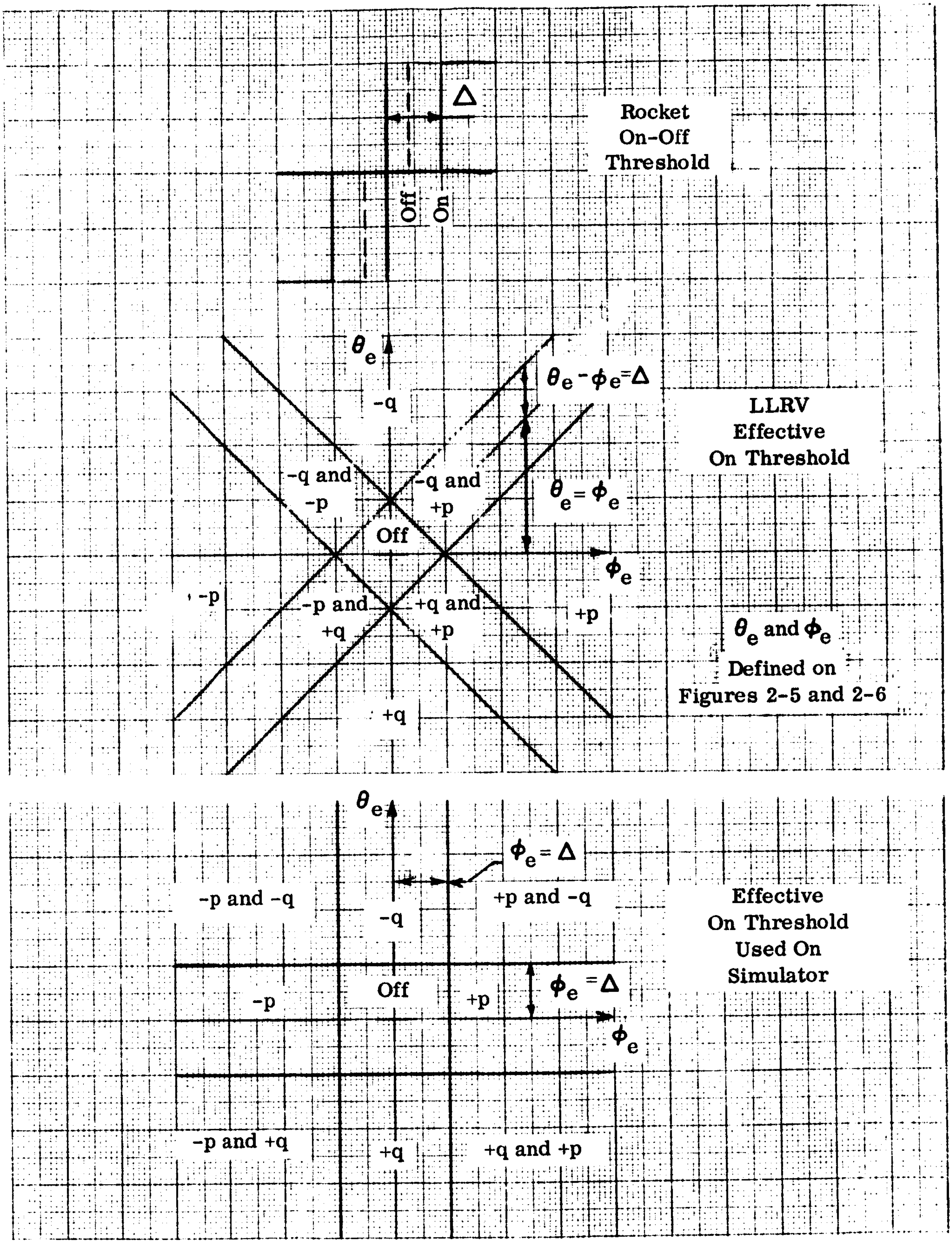


Figure 2-4. Attitude Control Rocket Threshold

Attitude Position Mode	Pilot Commands	ϕ_c	θ_c	ψ_c	$K_\phi = K_\theta = K_\psi = 0$
Attitude Rate Mode		p_c	q_c	r_c	$K_\phi = K_\theta = K_\psi =$
Attitude Acceleration Mode		$\dot{p}_c$	$\dot{q}_c$	$\dot{r}_c$	$K_p = K_q = K_r = 0$

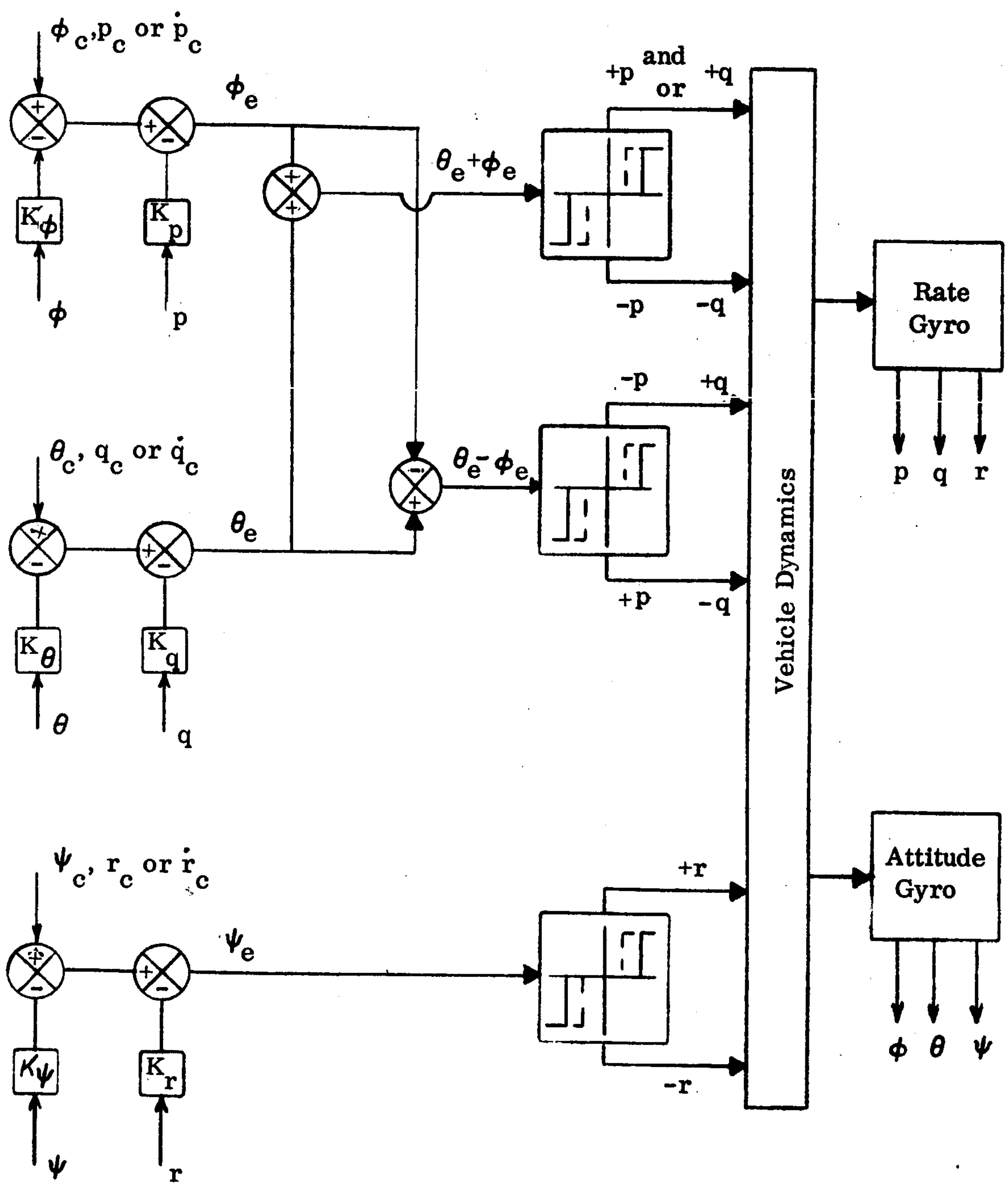


Figure 2-5. LLRV Attitude Control System Block Diagram

	Pilot Commands	
Attitude Position Mode	ϕ_c, θ_c, ψ_c	
Attitude Rate Mode	p_c, q_c, r_c	$K\phi = K\theta = K\psi = 0$
Attitude Acceleration Mode	$\dot{p}_c$, $\dot{q}_c$, $\dot{r}_c$	$K\phi = K\theta = K\psi = K_p = K_q = K_r = 0$

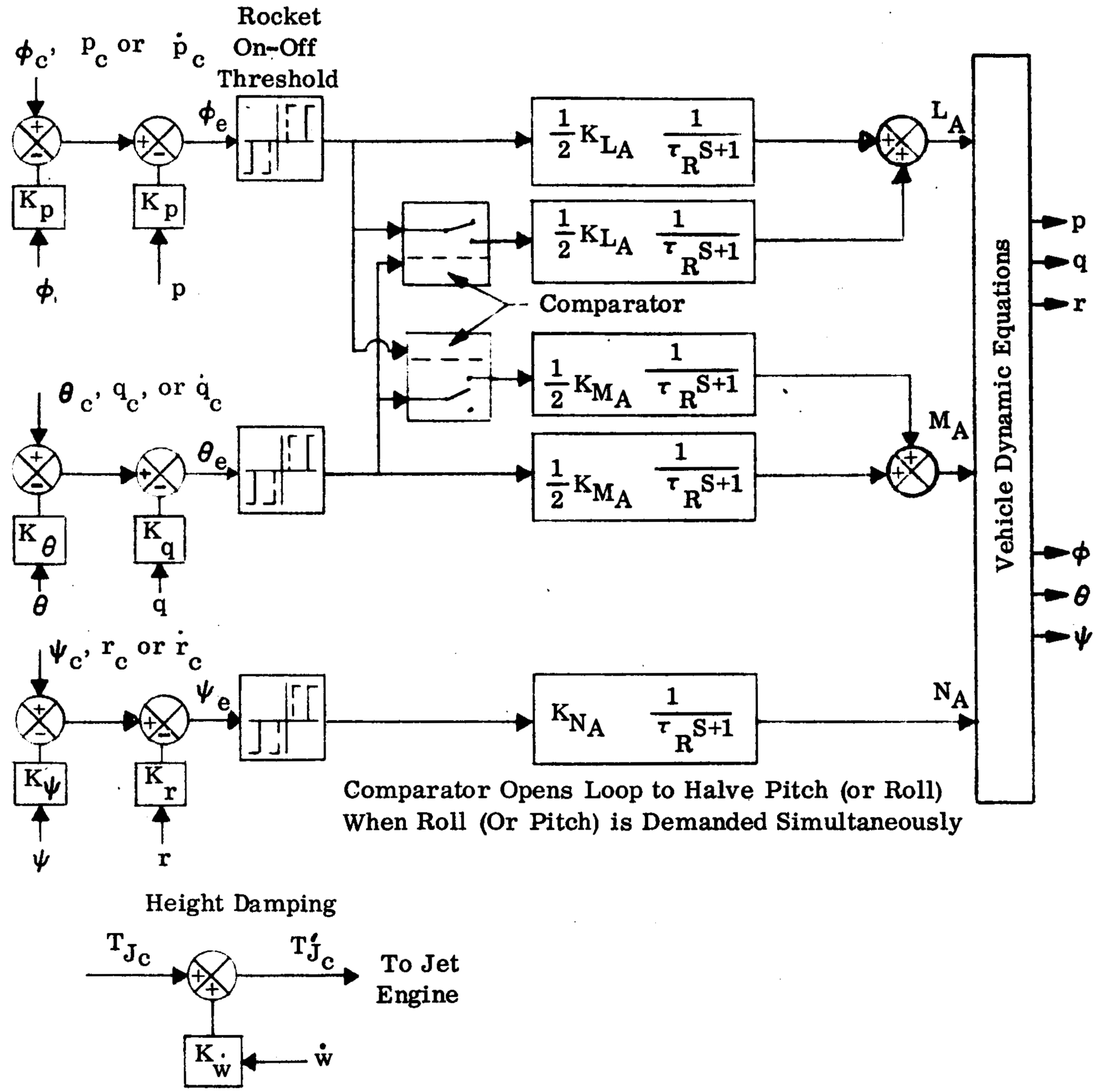


Figure 2-6. Simulator Attitude Control System Block Diagram

2.3.4.1. Attitude Acceleration Command. - With this mode of control there are no vehicle rate or position feedbacks i.e., K_{ϕ}, K_{θ}, K_{ψ} and K_p, K_q, K_r are all zero. Signals from the pilot's controls go directly to the on-off threshold. When the signal exceeds the ON threshold, the appropriate rockets fire, producing an acceleration in roll, pitch, or yaw which is independent of further stick movement until the control is returned to a deflection less than the equivalent OFF threshold.

This "all or nothing" characteristic makes the vehicle very difficult to control since, when flying with steady moments acting on the vehicle (e.g. pitching moments in forward flight), the pilot cannot use a steady stick deflection to maintain attitude but instead has to keep "pumping" the stick. The handling qualities study in fact found that it was not possible to control the vehicle in this mode. See Paragraph 3.7.

2.3.4.2. Attitude Rate Command. - This mode is a pseudo-proportional control. The rockets are still either on or off, but the rate of rotation developed is proportional to the stick deflection. This is achieved by taking the signals from the rate gyro, which represent the measured rates of rotation of the vehicle about the vehicle body axes (i.e., p, q, r), multiplying by the appropriate gain K_p, K_q, K_r (see Figure 2-5), and then subtracting from the input signal out of the pilot's control. Thus for a steady control deflection the vehicle will achieve a steady rate of rotation defined by:

e.g. roll $$p_c - K_p p = 0$$

This defines stick sensitivity:

$$p_c = K_s \delta_s = K_p p \qquad p = \frac{K_s \delta_s}{K_p}$$

Where K_s = stick gain $\frac{\text{rad/sec}}{\text{inch}} = \frac{1.0 \text{ rad/sec}}{5.6 \text{ inch}}$ in simulation

δ_s = stick deflection - inches

This mode was found flyable with various values of stick sensitivity, on-off threshold, and control power.

2.3.4.3. Attitude Position Command. - This mode also is pseudo-proportional. The rate and position gyros are combined with the pilot's control input. This results in a given control position maintaining the vehicle at a corresponding attitude.

e.g., in the steady state: $$\phi_c - K_p p - K_{\phi} \phi = 0$$

This mode of control was very easy for the pilot to fly. Checks were conducted on the open loop dynamics (no pilot) to ensure that the attitude and rate gains gave a stable overall system and the attitude control rocket thresholds were adjusted to minimize rocket pulse rates. Satisfactory attitude rate and position gains were:

$$K_\phi, K_\theta, K_\psi = 1.0$$

$$K_p, K_q, K_r = 0.5$$

Rocket pulsing will be different on the LLRV from that simulated because of the introduction of a diode in parallel with the on-off solenoid. This prolongs the rocket thrust decay time.

2.3.4.4. Summary. - It will be noted that all three types of control modes utilize the same basic electronics and rockets for aerodynamic moment compensation and for pilot commanded attitude changes. Thus, at high speeds, some of the available control power is being used to overcome the aerodynamic moments.

In the acceleration command mode, the pilot senses the aerodynamic moments constantly trying to rotate the vehicle and compensates by means of short bursts from the control. In the rate mode, the aerodynamic moments are almost indistinguishable to the pilot because, when the angular rate defined by the stick deflection and the on-off threshold is reached, the rockets automatically fire to prevent this rate from being exceeded. When flying with the attitude position command mode, the aerodynamic moments are almost completely compensated and a given stick deflection will hold the vehicle's attitude within the limits defined by the effective on-off threshold.

2.4. JET ENGINE AND LIFT ROCKET CONTROL MODES.

There are two primary modes of jet engine and lift rocket control. These are: (1) the lunar simulation mode in which the turbojet engine is automatically controlled to overcome aerodynamic drag and provide a vertical lift equal to 5/6 of the LLRV weight, while the pilot controls the lift rocket thrust; (2) the engine centered mode in which the engine is maintained aligned with the vehicle centerline while the pilot controls the thrust level and the lift rockets are off. However, from the point of view of systems there are two other modes, one of which is to protect the engine in case of tilt angles exceeding the permissible range for satisfactory engine lubrication and the other is to lock the gimbal in case of failure in the normal gimbal actuating system. A brief description and summary of the four modes is given in the following paragraphs.

(1) Local Vertical Mode. - The automatic system keeps the engine aligned with the local vertical:

   (1) This is used when the vehicle is on the ground

   (2) When flying in the engine centered mode or lunar simulation mode, if the engine deviates more that 14 degrees from the vertical this mode is automatically established after a nominal time delay (0.5 sec).

(2) Engine Centered Mode. - The automatic system keeps engine aligned with the vehicle centerline. This is used to fly to a point where a lunar simulation is to be initiated or to return to base after a simulation.

(3) Lunar Simulation (or Jet Stabilization) Mode. - This is used during lunar simulation. The automatic system tilts the engine and modulates the thrust so that the engine supports 5/6 of the instantaneous weight and overcomes the aerodynamic drag. Maximum tilt angle of the engine is limited to 40° from the vehicle (outer frame) body axes or 14 degrees from the local vertical.

(4) Emergency Gimbal Locked Mode. - An independent hydraulic valve and pressure source aligns the engine with the vehicle center line:

   (1) When engine stabilization system malfunctions, the automatic system first switches to the Local Vertical Mode; if engine is not brought to vertical within a nominal time (0.5 sec) the system sequences to this locked mode automatically.

   (2) Pilot can select locked mode manually. In this case there is no time delay.

2.5. PRIMARY FLIGHT CONTROLS.

Briefly the primary flight controls consist of the following:

Pitch and Roll control	- center stick
Yaw control	- conventional rudder pedals
Jet engine throttle	- conventional throttle quadrant on pilot's console.
Lift rocket throttle	- helicopter type collective pitch stick on left-hand side

For details of these systems and the instrumentation, refer to the LLRV Flight Manual, Bell Aerosystems Company Report 7161-954005.

2.6. AERODYNAMIC CHARACTERISTICS.

The aerodynamic forces and moments are presented for reference only. Consult the Summary of Estimated Performance, Bell Aerosystems Company Report 7161-954003.

Using the following data; the drag, rolling, pitching, and yawing moments have been evaluated with the engine centered to indicate typical magnitudes for various velocities.

This data is shown on Figure 2-7 through 2-10 together with the corresponding data used for the configuration studied during the analog simulation.

2.6.1. Aerodynamic Forces and Moments on Vehicle Outer Frame. -

Forces

$$A_{v_x} = -1.965 \quad 1/2 \ \rho S \ u\sqrt{(u^2 + w^2)}$$
$$A_{v_y} = -1.709 \quad 1/2 \ \rho S \ v\sqrt{(u^2 + v^2)}$$
$$A_{v_z} = -1.830 \quad 1/2 \ \rho S \ v\sqrt{(u^2 + w^2)}$$

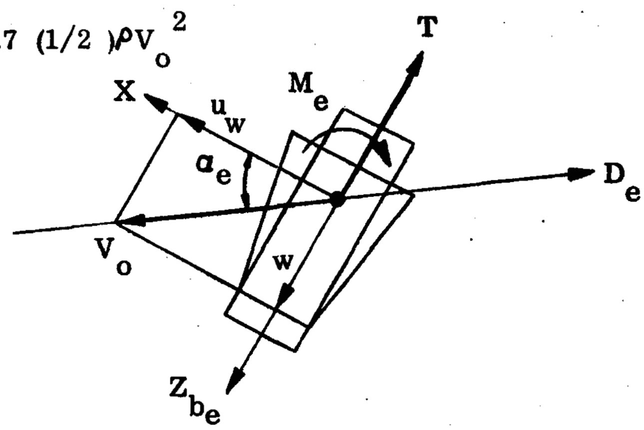
Moments (Equipment platform aft)

$$L_v = -0.172 \ (1/2 \ \rho SL) \ v\sqrt{(u^2 + w^2)}$$
$$M_v = -0.129 \ (1/2 \ \rho SL) \ u\sqrt{(u^2 + w^2)}$$
$$N_v = -0.340 \ (1/2 \ \rho SL) \ v\sqrt{(u^2 + v^2)}$$

2.6.2. Aerodynamic Forces and Moments on the Engine. - These forces and moments are in the plane of the resultant velocity V_o. To resolve into vehicle outer frame body axes components the method used in the simulator set up could be used (Paragraph 3.5).

Forces

$$D_e = \frac{\dot{W}}{g} u_w + 11.7 \ (1/2)\rho V_o^2$$



$$\text{where } \dot{W} = 24.5 + 36.6 \left(\frac{T_j}{1000}\right) - 3.303 \left(\frac{T_j}{1000}\right)^2 \frac{\text{lb}}{\text{sec}}$$

Moments

$$M_{u_e} = \frac{\dot{W}}{g} w \, x_{cp}$$

$$\text{where } x_{cp} = 2.2855 \left(1 + 0.5109 \frac{w}{V_o}\right)$$

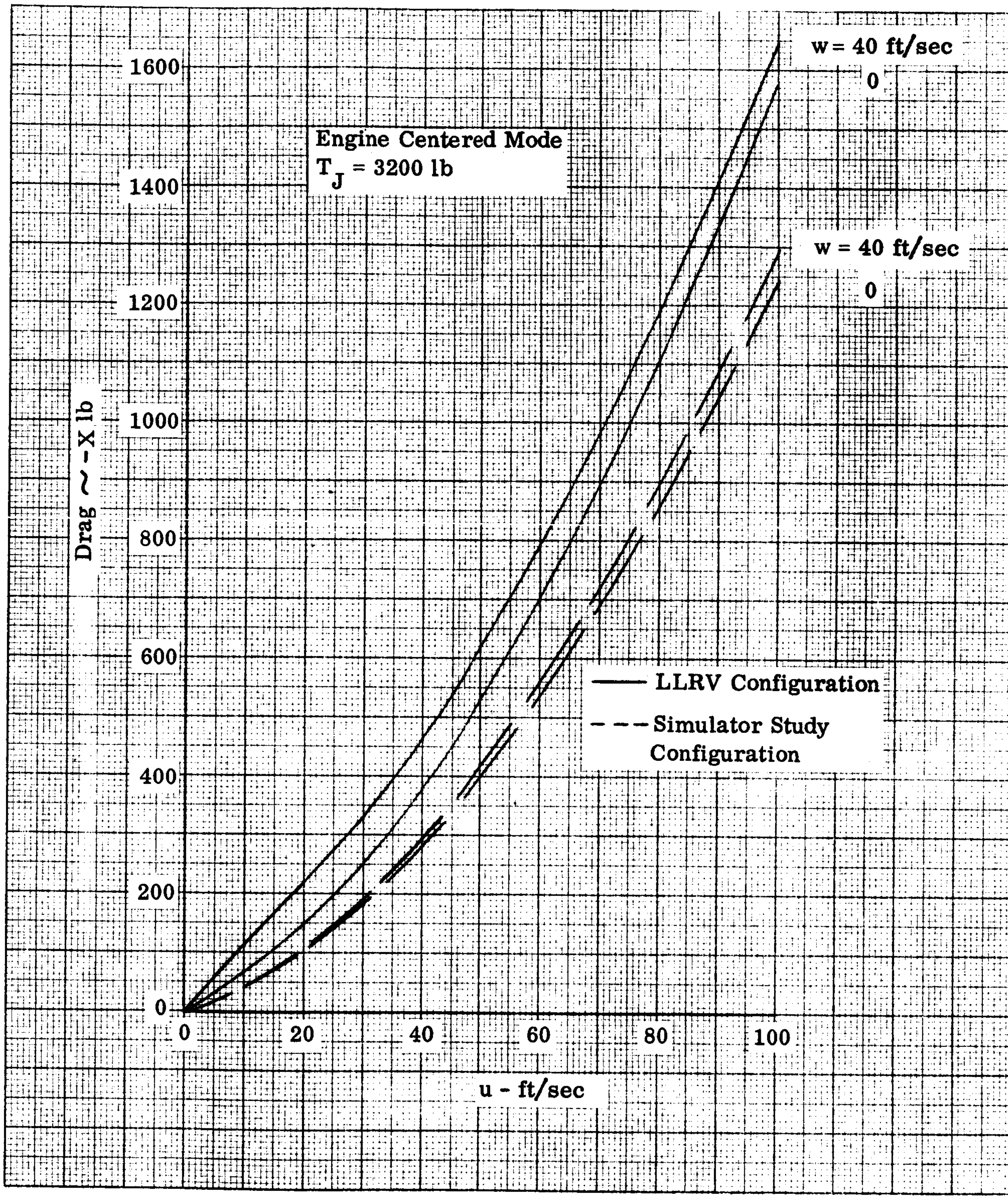


Figure 2-7. LLRV Drag

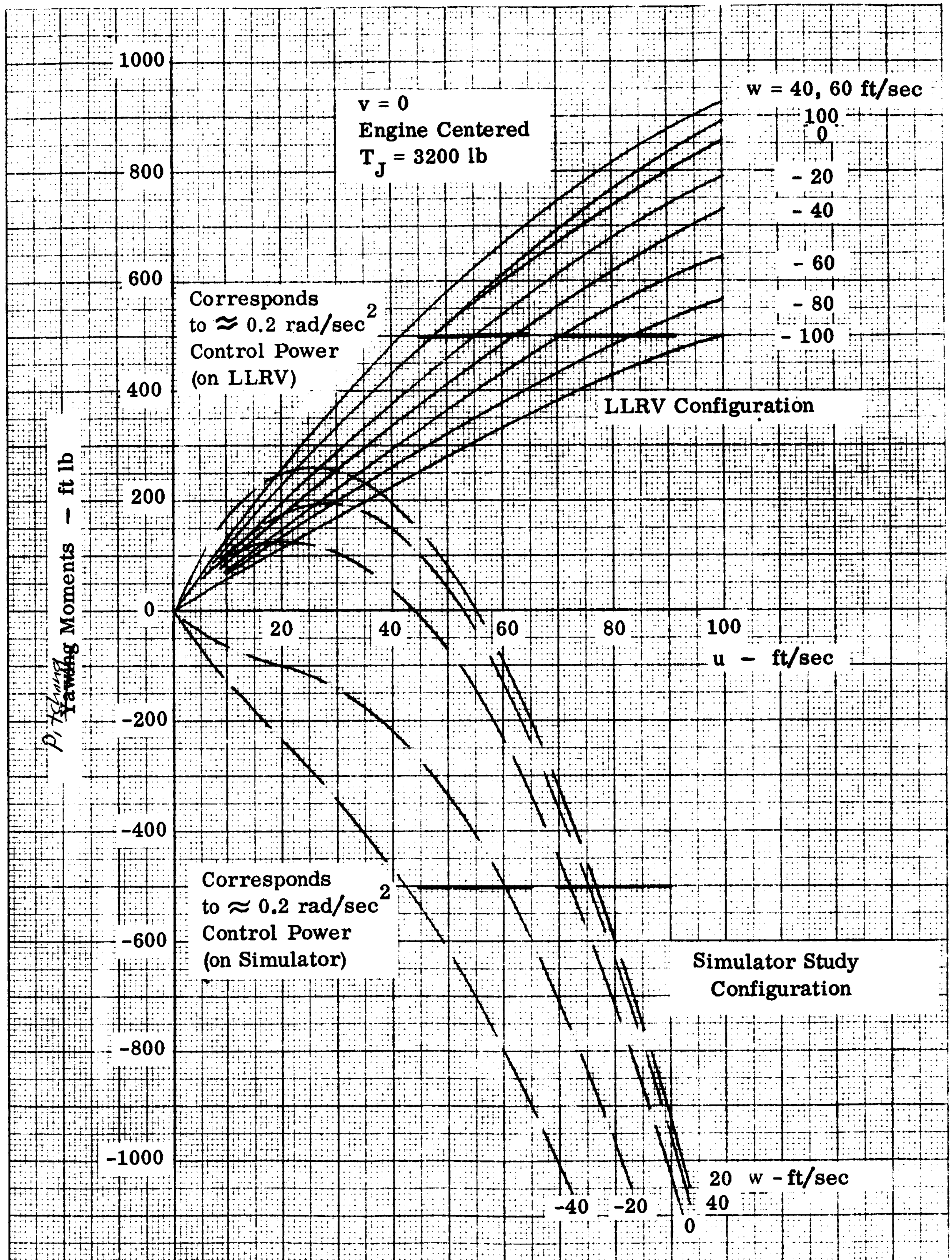


Figure 2-8. Pitching Moments

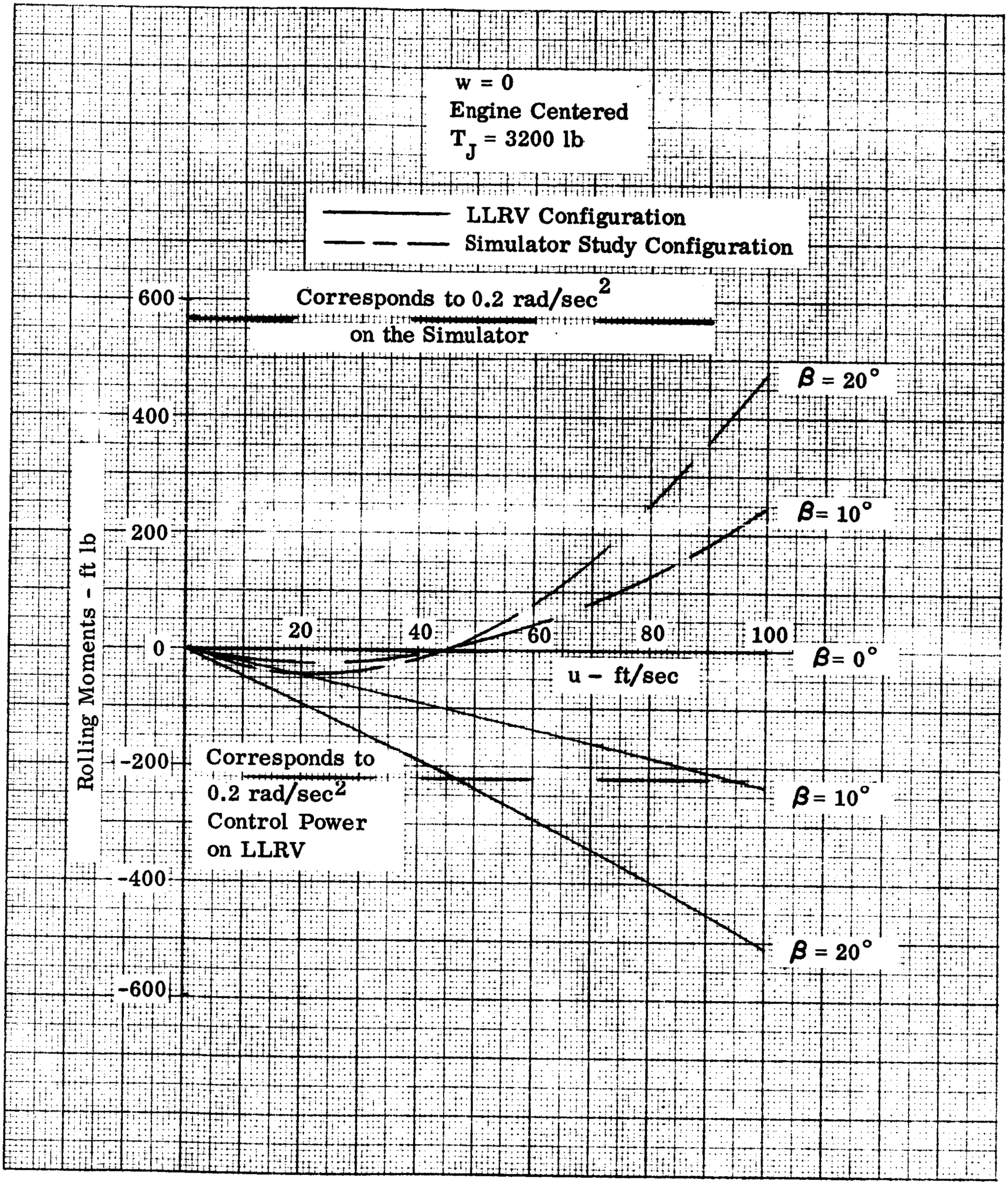


Figure 2-9. Rolling Moments

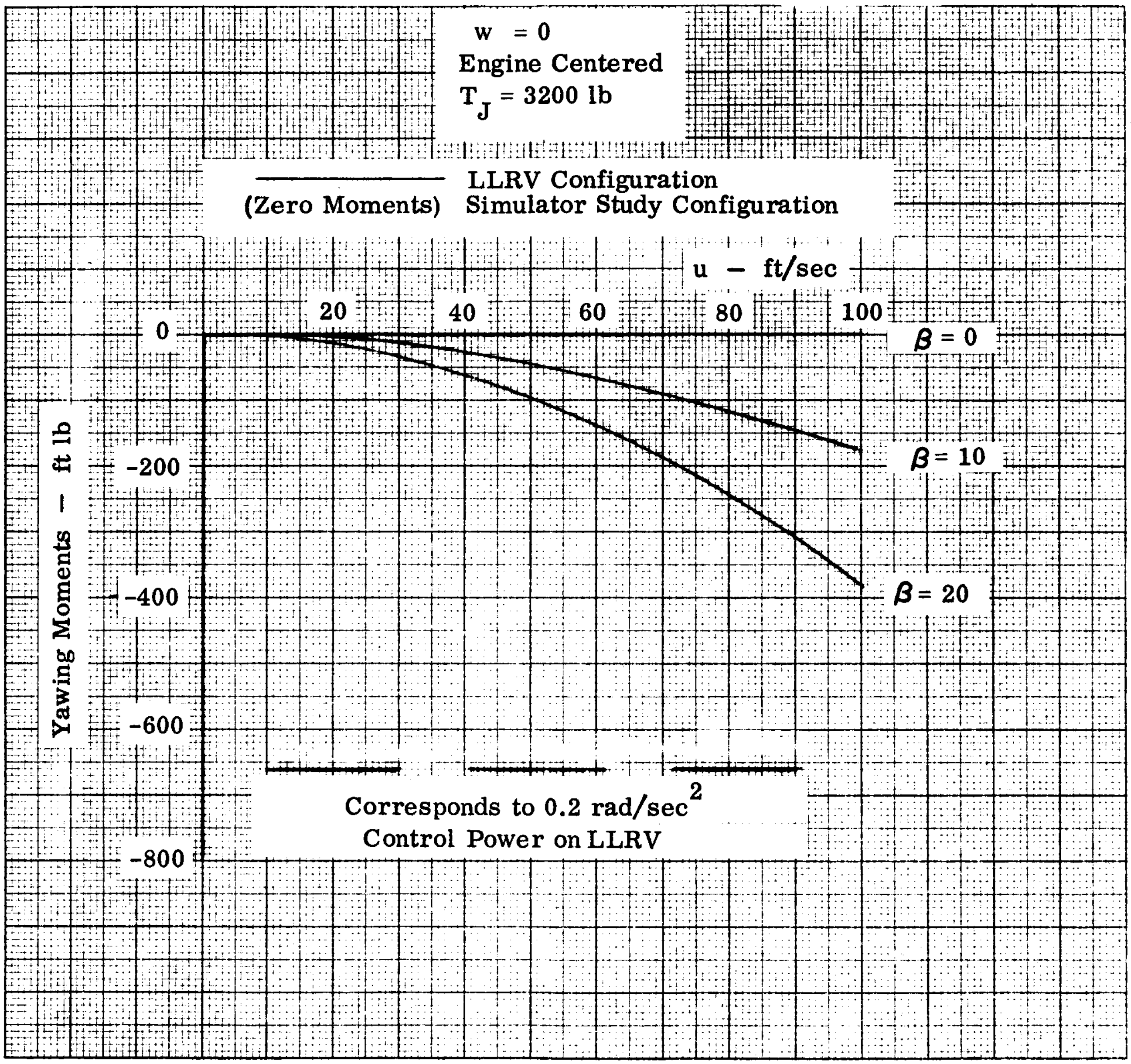


Figure 2-10. Yawing Moments

SECTION III

PILOTED ANALOG SIMULATOR STUDY

3.1. METHODS AND PHILOSOPHY OF APPROACH.

The piloted simulator study was carried out to assess the handling qualities of the LLRV using on-off type attitude control rockets instead of the more usual proportional type and also to obtain design parameters such as the attitude control fuel consumption rate. Aerodynamic forces and moments were incorporated and both the engine centered mode and lunar simulation mode could be simulated.

Since this study was carried out, the LLRV design has incorporated a major configuration change. This changed the aerodynamic forces and moments (particularly the yawing moments) and, to a large extent, means that the handling qualities results must now be considered as qualitative rather than quantitative. Other design refinements include changes in the rocket on-off threshold (see Figure 2-4 and Paragraph 4.1) and different flight instruments.

The simulator was of the fixed-base type and set up in six degrees of freedom. The parameters simulated and the methods used are outlined in the following paragraphs.

3.2. PHYSICAL CHARACTERISTICS OF SIMULATED VEHICLE.

(1) Weight:

	Empty	1800 lb
	Fuel rocket (H_2O_2)	600 lb
	Fuel jet eng. (JP4)	400 lb
	Supported on gimbal (engine)	700 lb
	Gross	3500 lb

(2) Moments of Inertia:

slug, ft^2	Engine Centered Mode		Lunar Simulation Mode	
	Full Fuel	Empty	Full Fuel	Empty
I_{xx}	2870	2480	2788	2607
I_{yy}	2850	2570	2762	2481
I_{zz}	3240	2600	3217	2585

(3) Jet Engine: CF-700-2V turbofan (contra-rotating)

Max. thrust (standard day sea level) 4200 lb

Specific fuel consumption, 0.7 lb/hr/lb

Thrust response time constant, 0.5 second

(4) Lift Rocket:	Max. thrust	500 lb/rocket
	Specific Impulse	$122 \frac{\text{lb sec}}{\text{lb}}$
	Time Constant	0.04 second
(5) Attitude Rockets:	Thrust Range	9 to 90 lb
	Specific Impulse	$100 \frac{\text{lb sec}}{\text{lb}}$
	Time Constant	0.02 second
(6) Moment Arms:	Roll rockets	10.31 ft
	Pitch rockets	8.54 ft
	Yaw rockets	7.25 ft

3.3. SIMULATED VEHICLE AERODYNAMICS.

The vehicle aerodynamic data was as follows:

3.3.1. Aerodynamic Forces and Moments on Outer Frame. -

$$C_{x_w} = 0.07645 \; u_w V_o \text{ lb}$$

$$F_{z_w} = 0.061 \, w \, V_o \text{ lb}$$

$$My_w = 0.0589 \, u_w^2 - 0.264 \, u_w V_o \text{ ft lb}$$

where:

$u_w = \sqrt{u^2 + v^2}$ ft/sec, see Figure 3-1.

$V_o = \sqrt{u^2 + v^2 + w^2}$ ft/sec

C_{x_w} = Aerodynamic force component in $(-u_w)$ direction lb (see Figure 3-1)

F_{z_w} = Aerodynamic force component in (-w) direction lb (see Figure 3-1)

My_w = Pitching moment in plane (u_w, w) (see Figure 3-1) lb ft

Resolving these into vehicle body axis components, the forces become:

$$A_{x_v} = -C_{x_w} \frac{u}{u_w} = -0.0765 \, u \, V_o \text{ lb}$$

$$A_{y_v} = -C_{x_w} \frac{u}{u_w} = -0.0765 \, v \, V_o \text{ lb}$$

$$A_{z_v} = -F_{z_w} = -0.061 \, w \, V_o \text{ lb}$$

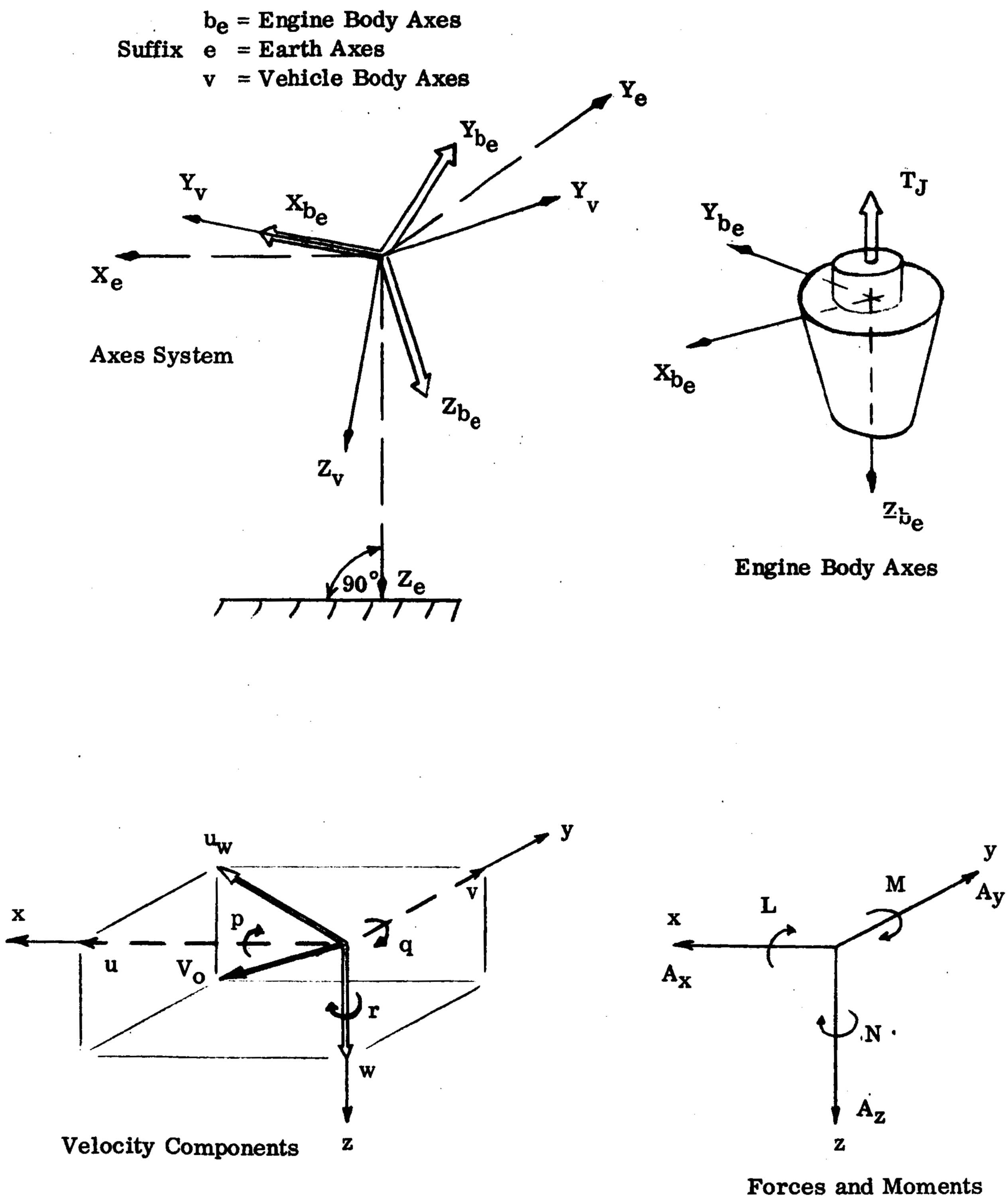


Figure 3-1. Definition of Axes Systems

and moments become:

$$L_v = M_{y_w} \frac{v}{u_w} = 0.0589\ v\ u_w - 0.264\ v\ V_o \ \text{ft lb}$$

$$M_v = M_{y_w} \frac{u}{u_w} = 0.0589\ v\ u_w - 0.264\ u\ V_o \ \text{ft lb}$$

$$N_v = 0$$

3.3.2. Aerodynamic Forces and Moments on Engine. -

(1) Forces. -

$$\frac{D}{V_o} = \frac{1}{2}\rho S\ C_{D_T}\ u_{w_e}\left[12.758 - 0.2022\ V_o + 0.001068\ V_o^2 \right]$$

and $F_{x_w} = \frac{D}{V} u_{w_e}$, $F_Z = D/V\ w_e$

Where C_{D_T} = thrust dependent drag coefficient

$= 0.296 + 0.000026T_J$

$$u_{w_e} = \sqrt{u_e^2 + v_e^2}$$

$$V_o = \sqrt{u_e^2 + v_e^2 + w_e^2} = \sqrt{u^2 + v^2 + w^2}$$

u_e, w_e, w_e = velocity components along engine body axes as illustrated in Figure 3-1.

Since the drag components are functions of the appropriate velocity components this drag was resolved directly into vehicle body axes directions using the appropriate velocity component, thus;

$$A_{x_e} = -\frac{D}{V_o} u,\ A_{y_e} = -\frac{D}{V_o} v,\ A_{z_e} = -\frac{D}{V_o} w$$

(2) Moments. - Equations used were:

$$M_{u_e} = \frac{1}{2}\rho S\ L_{ref}\ C_{m_T}\ u_{w_e}\left[\sqrt{u_{w_e}^2 - w_e^2} + 1.274\ w_e\right] \text{x}$$

$$\left[0.8569 - 0.0159\sqrt{u_{w_e}^2 + w_e^2} + 0.0000855\sqrt{u_{w_e}^2 + w_e^2} \right]$$

where M_{u_e} acts in the plane of u_{w_e} and w_e

and $C_{m_T} = 0.74 + 0.00047\ T_J$

$S = 38.4\ \text{ft}^2$

$L_{ref} = 7.0$ ft

(3) Engine Centered Mode. - For this condition, the engine body axes and vehicle (outer frame) body axes are coincident so that moments can be resolved directly in terms of vehicle body axes velocity components u, v, w:

$$M_e = M_{u_e} \frac{u_e}{u_{w_e}} = M_{u_e} \left(\frac{u}{u_w}\right)$$

$$L_e = -M_{u_e} \frac{v_e}{u_{w_e}} = -M_{u_e} \left(\frac{v}{u_w}\right)$$

Yawing moment was assumed to be zero.

(4) Lunar Simulation Mode. - In this mode the vehicle (outer frame) axes and engine body axes do not coincide since the engine is automatically stabilized in the vertical position or tilted sufficiently to overcome drag during translation.

Since the engine is not allowed to tilt more than 14 degrees from the vertical, the approximation was made, that:

$$w_e = \dot{z}_{earth} \text{ and } u_{w_e} = \sqrt{\dot{x}^2_{earth} + \dot{y}^2_{earth}}$$

Thus giving M_{u_e} in the earth axes u_{w_e} and z plane. Hence:

$$M_{u_{e_{earth}}} = M_{u_e} \frac{\dot{x}}{u_{w_e}}$$

$$L_{u_{e_{earth}}} = -M_{u_e} \left(\frac{-\dot{y}}{u_{w_e}}\right)$$

These earth axes components were transformed to vehicle (outer frame) body axes components using the Euler transformation sequence yaw ψ , pitch θ , and roll ϕ . This is summarized by the following matrix:

$$\begin{bmatrix} x_b \\ y_b \\ z_b \end{bmatrix} = \begin{bmatrix} \cos\theta\cos\psi & \cos\theta\sin\psi & -\sin\theta \\ \sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi & \sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi & \sin\phi\cos\theta \\ \sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi & \cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi & \cos\phi\cos\theta \end{bmatrix} \begin{bmatrix} x_e \\ y_e \\ z_e \end{bmatrix}$$

3.4. SIMULATED VEHICLE CONTROL SYSTEMS.

3.4.1. Attitude Controls. - Attitude control systems incorporated in the study were similar to those on the LLRV except for the difference in effective rocket threshold. (Refer to Paragraphs 2.3 and 4.1.) However, due to the reduced moment arms, the attitude control power for a given level of attitude rocket thrust is lower on the LLRV than was simulated (Table 3-1). This will probably result in increased attitude rocket fuel consumption rate.

TABLE 3-1

LLRV VERSUS SIMULATED VEHICLE
CONTROL POWERS

ITEM	LLRV CONFIGURATION*	SIMULATED VEHICLE
Maximum Gross Weight - pounds	3666	3500
Max. Roll Control Power/I_{xx} rad/sec^2	0.981	1.3
Max. Pitch Control Power/I_{yy} rad/sec^2	0.75	1.08
Max. Yaw Control Power/I_{zz} rad/sec^2	0.479	0.8
*(See Figure 2-2)		

Only the BOTH configuration was simulated. This means that all attitude control moments were pure couples without the translational effects which occur when on STD or TEST. However, this translational acceleration cannot exceed 1.0 ft/sec^2 and was considered negligible.

3.4.2. Cockpit Controls and Instrumentation. -

3.4.2.1. Controls. - Flight controls consisted of the following:

Central stick	±6.0-inch travel in pitch and roll
Rudder pedals	±3.25-inch travel
Jet engine throttle	Conventional quadrant type with approximately 45 degrees travel at 2.0-inch minimum radius.
Lift rocket throttle	Floor mounted collective - pitch type lever. Travel about 20 degrees from horizontal to 60 degrees from horizontal. Length of lever approximately 16 inches.

3.4.2.2. Instrument Display. - The cockpit instrumentation was as shown in Figure 3-2.

Distance travelled was indicated by an earth axes x, y plotter.

Vehicle (outer frame) body axes u and v velocity components were shown on an oscillograph.

Vehicle roll, pitch and yaw attitude were indicated on another oscillograph.

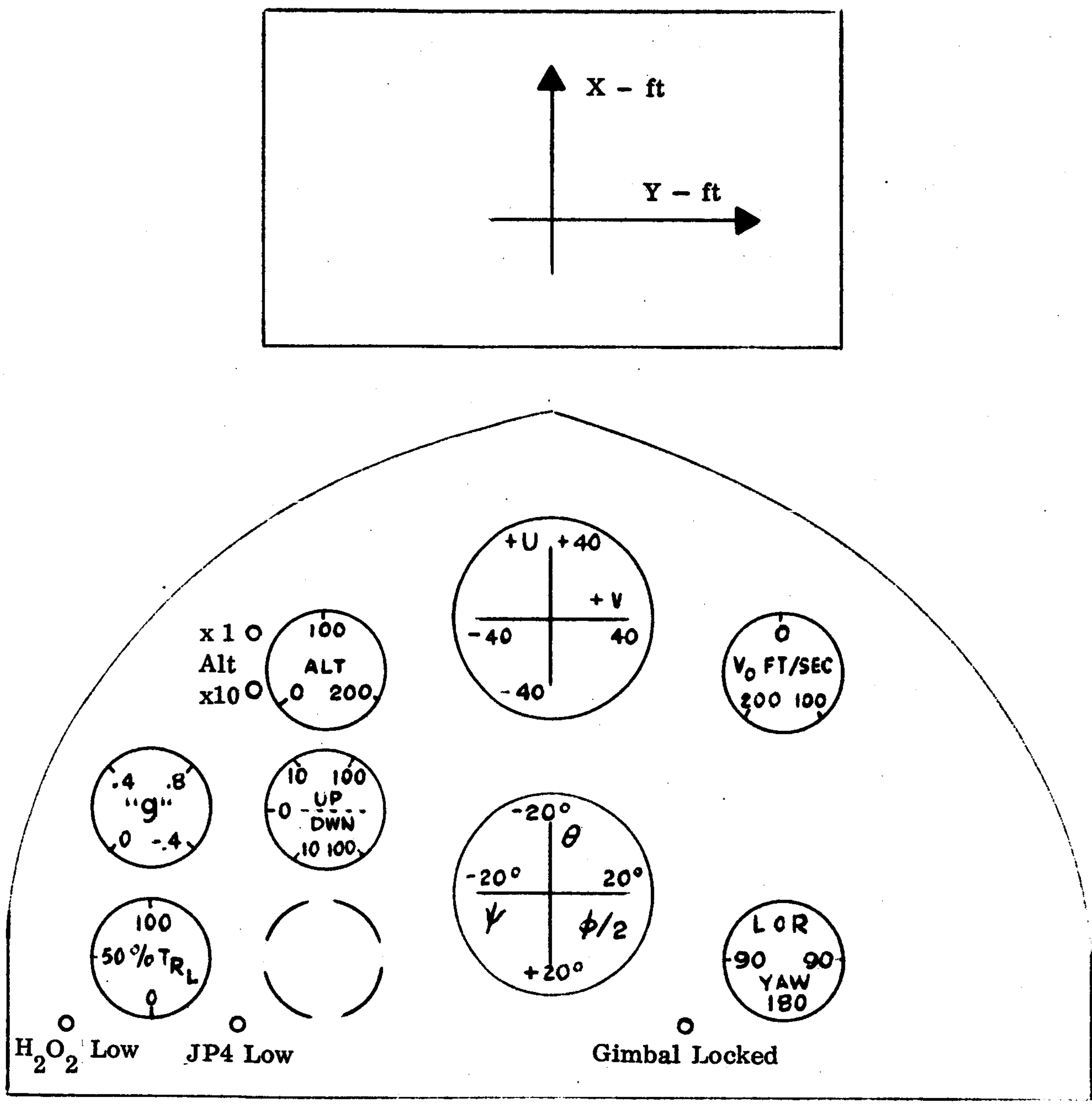


Figure 3-2. Simulator Cockpit Display

Other instruments indicated:

Altitude had dual range X1 and X10, V_o – ft/sec

Vertical acceleration ±g

Ascent or decent velocity

Percentage of lift rocket thrust being used

Coarse yaw angle indicator ±180 degrees

Fuel level warning lights for H_2O_2 and JP4 were set at 10% remaining.

3.4.2.3. Engine Stabilization. - For the lunar simulation mode, the engine control system was assumed to perfectly compensate aerodynamic forces and, in addition, provide a thrust equal to 5/6 vehicle weight acting in a direction perpendicular to the earth. Moments due to changing the engine attitude were neglected. A separate study was carried out to assess the engine stabilization system and the moments due to actuating the engine were found to be small.

3.5. EQUATIONS OF MOTION.

The equations of motion are for the vehicle (outer frame) body axes system. (See Figure 3-1.)

3.5.1. Force Equations.-

X direction $m(\dot{u} - rv + qw) = A_{ex} + A_{vx} + mg_x + T_{J_x}$

Y direction $m(\dot{v} - pw + ru) = A_{ey} + A_{vy} + mg_y + T_{J_y}$

Z direction $m(\dot{w} - qu + pv) = A_{ez} + A_{vz} + mg_z + T_{J_z} + T_{R_L}$

3.5.2. Moment Equations.-

Roll: $L_{D_e} + L_{D_v} + L_p + L_A = I_{xx}\dot{p} + (I_{zz} - I_{yy})qr$

Pitch: $M_{D_e} + M_{D_v} + M_q + M_A = I_{yy}\dot{q} + (I_{xx} - I_{zz})\,rp$

Yaw: $N_{D_e} + N_{D_v} + N_r + N_A = I_{zz}\dot{r} + (I_{yy} - I_{xx})\,pq$

3.5.3. Assumptions Made for Derivation of Equations of Motion. -

(1) Changes in moments of inertia and products of inertia due to engine rotation relative to the vehicle (outer frame) body axes are negligible.

(2) Effects of angular velocities of the jet engine are negligible in the lunar simulation mode.

(3) Vehicle (outer frame) center of gravity coincides with the gimbal axes origin.

(4) Changes in moments of inertia due to fuel consumption were accounted for by assuming a linear change from the value with full fuel to the value with zero fuel, i.e.,

$$I_t = I_{full} - \left(I_{full} - I_{empty}\right)\left(\frac{W_{fuel\ remaining}}{W_{full} - W_{empty}}\right)$$

(5) Aerodynamic rate damping terms $L_p p$, $M_q q$, $N_r r$, are negligible.

3.6. TEST PROCEDURE.

Three pilots took part in these evaluations. Two were company test pilots, both having helicopter experience, and one had, in addition, VTOL aircraft flight test experience and considerable previous flight simulator experience. The third pilot is an ex-Navy pilot. The experience of the pilots is outlined in Table 3-2.

TABLE 3-2

PILOT BACKGROUND EXPERIENCE SUMMARY

PILOT	TOTAL FLYING HOURS	HELICOPTER HOURS	OTHER VTOL HOURS	PREVIOUS SIMULATOR HOURS	NUMBER OF RUNS IN THIS PROGRAM
A	3600	100	—	100	98
B	4800	600	13 (90 landings)	500	33
C	1400	—	—	100	16

The program was conducted in three phases. The first phase was a "loose" preliminary mission intended to give some qualitative and quantitative data as quickly as possible. It was commenced after approximately four hours of pilot learning time. The second phase involved a more closely defined descent mission. The third phase consisted of qualitative investigations of such things as recovery from system failures.

3.6.1. <u>Preliminary Mission.</u> - The preliminary mission flown by the pilots was defined as:

(1) Start at zero attitude, speed and height.

(2) Climb vertically to approximately 200 ft.

(3) Accelerate forward to approximately 35 ft/sec.

(4) Decelerate and accelerate backward to 35 ft/sec.

(5) Decelerate to zero speed and descent.

(6) The mission time to be limited to approximately two minutes.

After the flight, recordings were made of the following parameters:

(1) Pilot ratings of attitude control and height control, based on the standard NASA Cooper scale, Table 3-3.

(2) Fuel consumed by the jet engine, lift rockets, and attitude rockets.

(3) Time for the mission.

Missions were flown in the lunar simulation mode and engine centered mode. Effects of the following parameters were investigated using the attitude rate command mode with feedback gains $K_p = K_q = K_r = 1$ (to give stick and pedal sensitivity of 1.0 rad/sec for full travel.).

(1) Pitch, roll and yaw control power.

(2) Attitude rocket on-off thresholds.

3.6.2. Descent Mission. - For this phase of the program, the pilots were asked to fly the following mission, (See Figure 3-3;)

(1) Start at zero attitude and zero speed, at a height of 1,000 feet.

(2) Make a controlled descent, stabilizing at approximately 20 ft/sec forward speed and 20 ft/sec rate of descent.

(3) Bring the vehicle to hover at approximately 100 feet above the landing area. The landing area being a 200-foot square with its center 1,000 feet directly ahead of the starting position.

(4) Maintaining a position over the landing area, descend and touch down with velocities less than 5.0 ft/sec in translation and descent.

(5) The mission to be accomplished as quickly as possible, and in any event within two minutes.

After each mission, the following observations were made:

(1) Pilot opinion ratings of attitude control and height control, based on the NASA Cooper scale (Table 3-3).

(2) Fuel consumed by the jet engine, lift rockets, and attitude control rockets.

TABLE 3-3

COOPER PILOT-OPINION RATING SYSTEM

OPERATING CONDITIONS	ADJECTIVE RATING	NUMERICAL RATING	DESCRIPTION	PRIMARY MISSION ACCOMPLISHED	CAN BE LANDED
Normal Operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
		4	Acceptable, but with unpleasant characteristics	Yes	Yes
Emergency Operation	Unsatisfactory	5	Unacceptable for normal Operation	Doubtful	Yes
		6	Acceptable for emergency condition only*	Doubtful	Yes
		7	Unacceptable even for emergency condition*	No	Doubtful
No Operation	Unacceptable	8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

*Failure of a stability augmenter

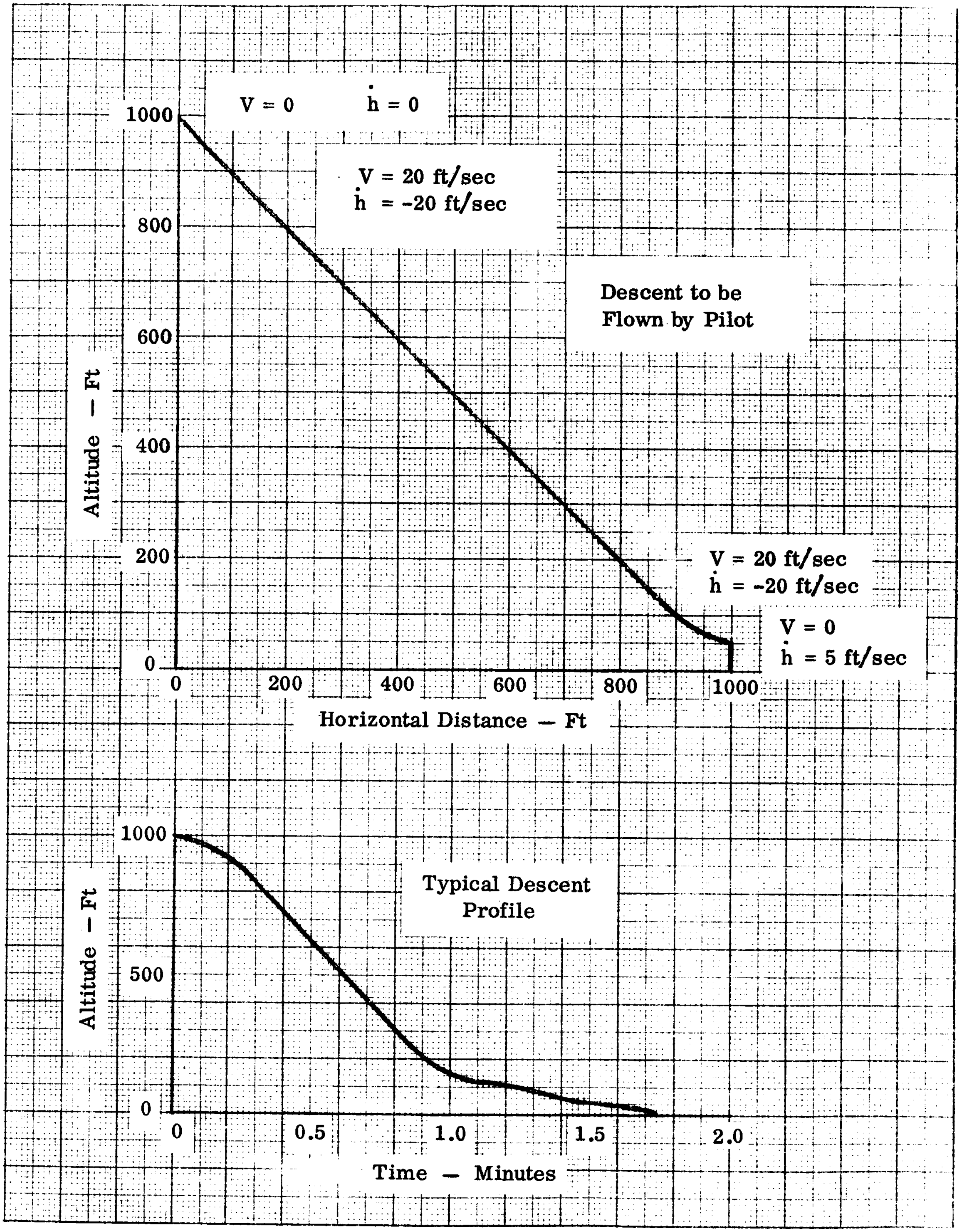


Figure 3-3. Descent Mission Profile

(3) Touch down position, rate, and attitude.

(4) Time for the mission.

Missions were flown with the attitude rate command system in combination with lunar simulation mode and engine centered mode.

Effects of the following parameters were studied:

(1) Pitch and roll control power. These were set equal to each other.

(2) Attitude rockets on-off thresholds.

(3) Rate feedback gain (stick sensitivity) - (See Figure 2-6).

3.6.3. Miscellaneous Investigations. - This part of the program consisted of miscellaneous investigations more qualitative than quantitative in nature.

3.6.3.1. Failure Modes. - Two types of failure were investigated: (1) jet engine failure; and (2) jet engine attitude control failure.

(1) Jet Engine Failure. - The nature of the simulation setup limited this investigation to the engine centered mode. The lift rocket maximum thrust was set to the emergency level of 4,000 pounds; this being controlled via the collective pitch lever in the usual way.

Failure was simulated by removing all jet engine thrust while pilot was translating at an altitude of approximately 1,000 feet. To simulate the emergency parachute, the descent rate was limited to 100 ft/sec. This is an approximation because the parachute drag at descent velocities less than 100 ft/sec is not simulated. The pilot was asked to control attitude and to touch down gently by applying full lift rocket thrust at the appropriate altitude-approximately 350 feet. See Figure 3-4 for approximate recovery boundaries.

This maneuver was also attempted with the throttle levers interchanged - i.e., the jet engine throttle controlling the lift rockets and vise versa.

(2) Jet Engine Stabilization Failure. - When flying in the lunar simulation mode, a failure of the jet engine stabilization system causes the gimbal to be returned to the local vertical or to the engine centered position and locked (Paragraph 2.4).

The effect of this on the vehicle will be moments caused by the reaction to the engine actuation and in going to the engine centered mode, if the vehicle (outer frame) is tilted, a sudden increase in horizontal acceleration. On the present simulation it was assumed that the engine went immediately to the centered position, and only the effects of horizontal acceleration were reproduced. The pilot's response to this was investigated.

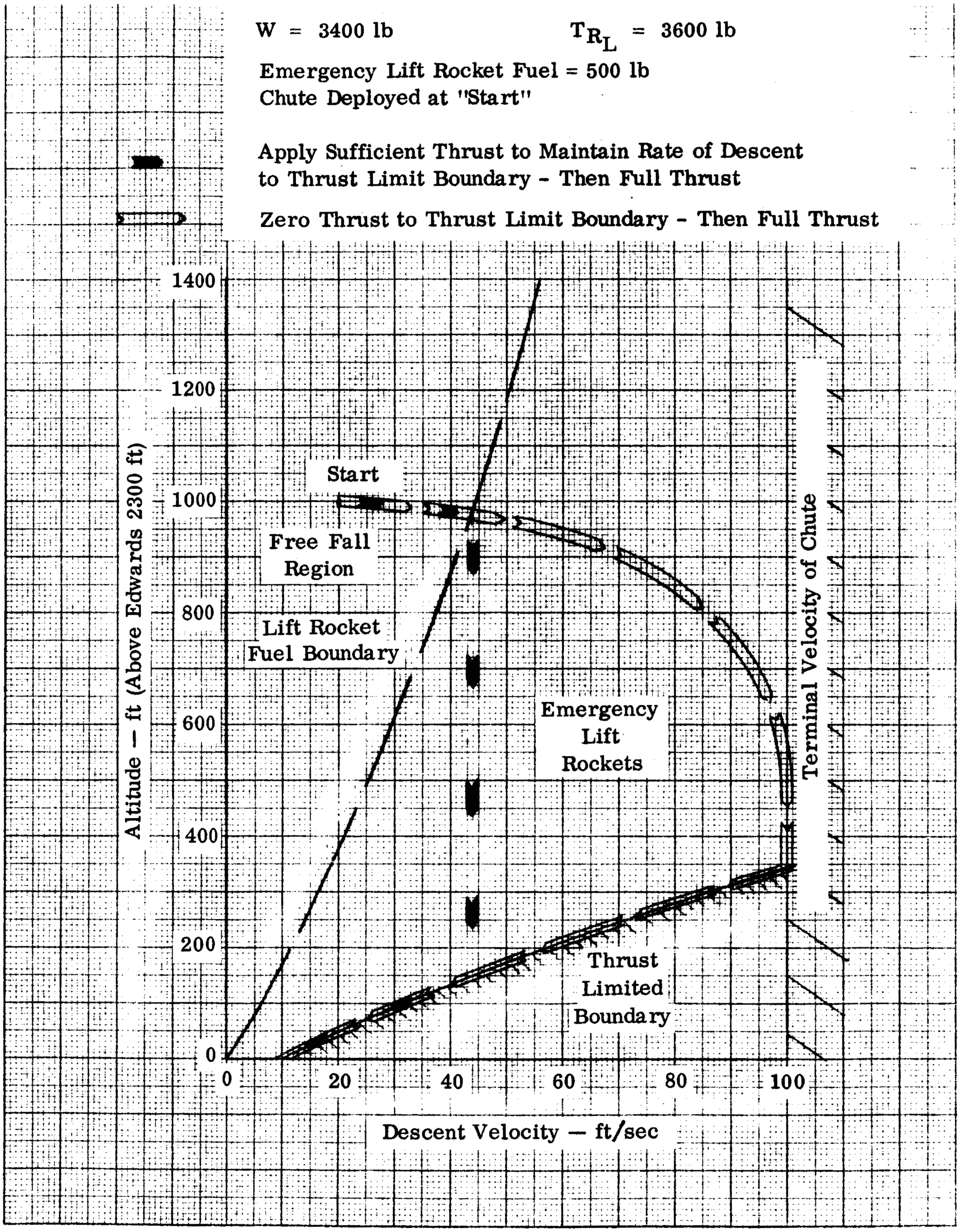


Figure 3-4. Jet Engine Failure Recovery Boundary

3.6.3.2. Attitude Position Command System. - This mode of attitude control was not considered critical to the design. Missions were therefore carried out with a nominal configuration to confirm the belief that attitude control in this mode is a very simple task. Fuel consumption rates were recorded to determine if there were any marked differences in the rate of attitude rocket fuel consumption using the position command mode rather than the rate command mode.

3.6.3.3. Takeoff Simulation. - A series of runs were performed in the attitude rate mode, engine centered, to obtain an idea of the minimum fuel consumption likely to be achieved during take-off and climb or translation. These climbs consisted of takeoff, climb to 1500 feet, and translation with a minimum of maneuvering. Flight time was limited to four minutes and fuel consumed was noted upon reaching altitude and after the four minutes.

3.6.3.4. Increased Aerodynamic Moments. - To obtain further indications of the effect of aerodynamic characteristics on the handling qualities of the vehicle, descent missions were carried out with the moments on the vehicle and engine doubled individually and together. This was carried out for the lunar simulation mode and for the engine centered mode.

3.6.3.5. Interchange of Lift Engine Throttles. - To determine the effect of using the conventional throttle quadrant to control the lift rockets in the lunar simulation mode, the functions of the two throttles were interchanged.

3.6.3.6. Height Damping. - In view of the difficulties experienced by the pilots in maintaining height control, it was decided to investigate the effects of height damping (engine centered mode). The mechanization achieved as indicated in Figure 2-6. Descent missions were then flown to determine the effect on pilot rating.

3.7. RESULTS AND DISCUSSION.

3.7.1. Attitude Control. - As far as possible, the pilots rated the ability to control attitude separately from the thrust-height control. However, it should be pointed out that the worst rating of the two would be applicable to the whole vehicle.

3.7.1.1. Preliminary Mission. - The results from the preliminary mission showed considerable scatter, both between the various pilots and for each pilot, see Figures 3-5 and 3-6. Most of this can be attributed to pilot learning effects and therefore only qualitative conclusions can be drawn from these data.

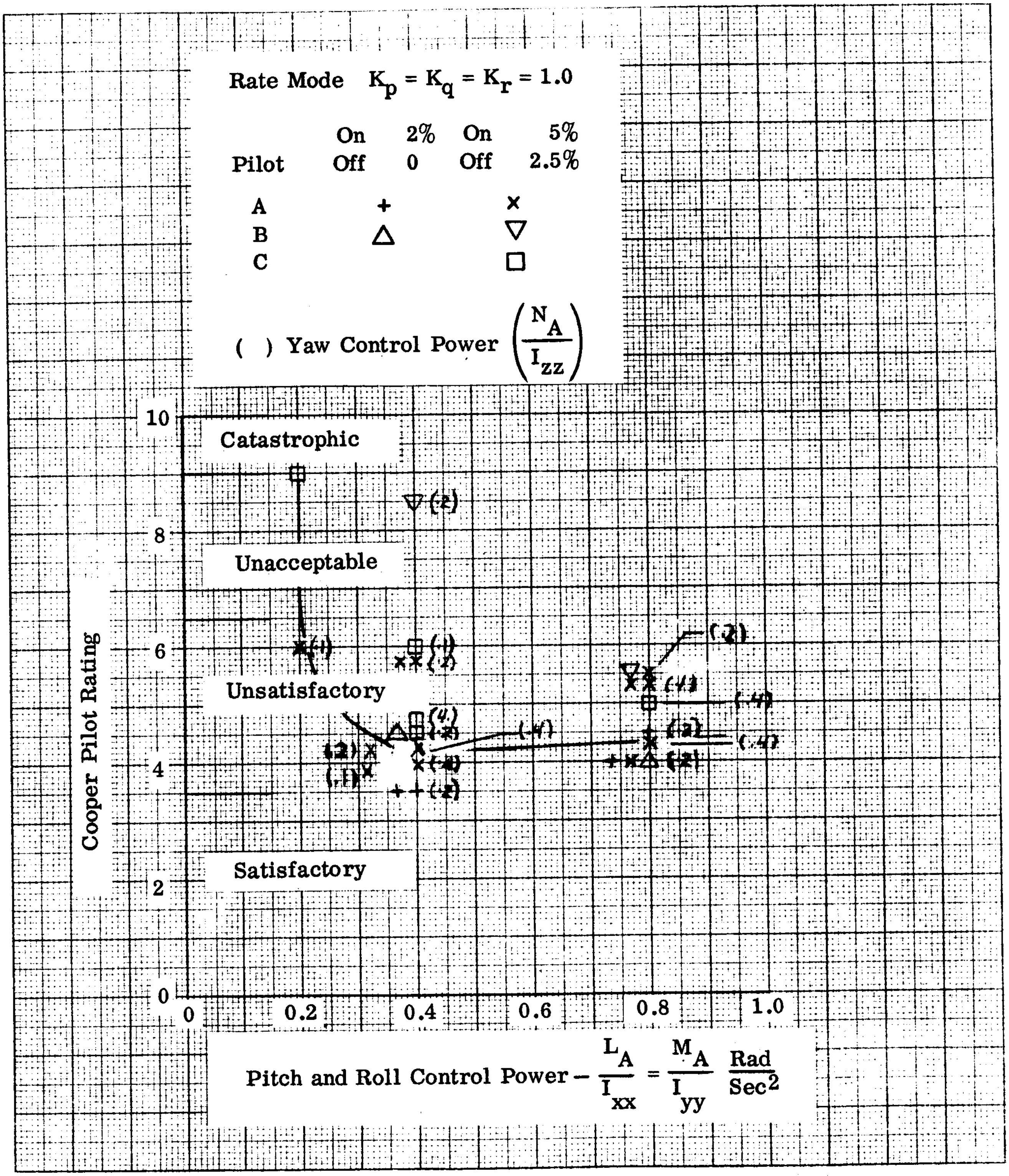


Figure 3-5. Pilot Rating - Preliminary Mission - Lunar Simulation Mode

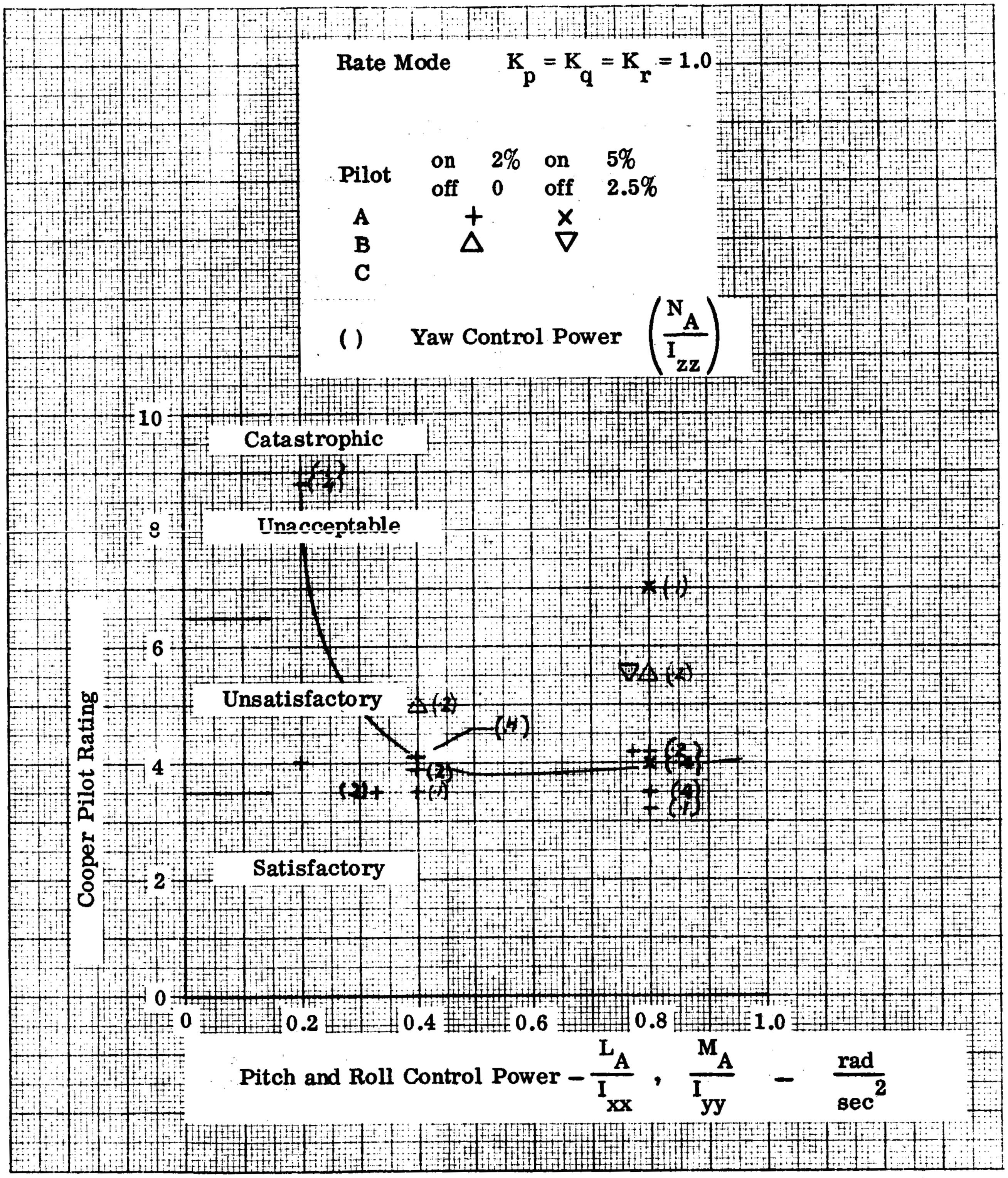


Figure 3-6. Pilot Rating - Preliminary Mission Engine Centered Mode

(1) Vehicle is not flyable with pitch and roll control power of 0.1 rad/sec^2.

(2) Yaw control power level had no significant effect in the range 0.1 to 0.4.

(3) Reducing the rocket on-off thresholds (with stick sensitivity set at full stick, i.e., -1.0 rad/sec) from on at five percent stick and pedal travel, off at two percent to on at two percent, off at zero, gave a marked improvement in the pilot's ability to control.

(4) Locking the gimbal appeared to have little or no effect on the pilot rating in this mission. The descent mission however showed this conclusion was not applicable to all missions.

(5) Pilot learning effects seemed to dominate the results of this preliminary phase.

3.7.1.2. Descent Mission. - Pilot ratings of attitude control in the rate command mode are shown on Figures 3-7 and 3-8 for the lunar simulation mode and engine centered mode, respectively. These data are for the chosen basic case in which:

(1) Rocket on-off thresholds are on two percent stick travel and off at zero stick travel.

(2) Rate feedback gains $K_p = K_q = V_r = 1$. These gains correspond to stick sensitivity and rudder pedal sensitivity of one rad/sec for full deflection.

(3) Yaw control power $\frac{N_A}{I_{zz}} = 0.2$ rad/sec^2.

(4) Gimbal free the attitude control was rated at 3 to 4 with pitch and roll control powers greater than 0.3 rad/sec^2. With control powers less than 0.3 rad/sec^2 pilot ratings deteriorated to 6 to 7. Gimbal fixed the ratings were approximately 1.5 ratings poorer than gimbal free but showed a similar trend with control power change.

(5) The divergence in pilot opinion rating at the low control power (0.2 rad/sec^2) is apparently due to the maximum aerodynamic moments encountered approaching the magnitude of the control powers. In this condition, unless small attitude changes were maintained, the moments increased to a level which could not be compensated.

It should be noted that pitch and roll control powers of 0.1 rad/sec^2 were found in the preliminary mission to be completely unflyable, so were not repeated during the descents.

To illustrate the deterioration in rating caused by changing from the lunar simulation mode to engine centered mode, the combined data has been plotted on Figure 3-8. The main reason for the lower ratings in the engine centered mode is the difficulty of controlling translation when the whole thrust vector is rotated during an attitude change instead of 1/6

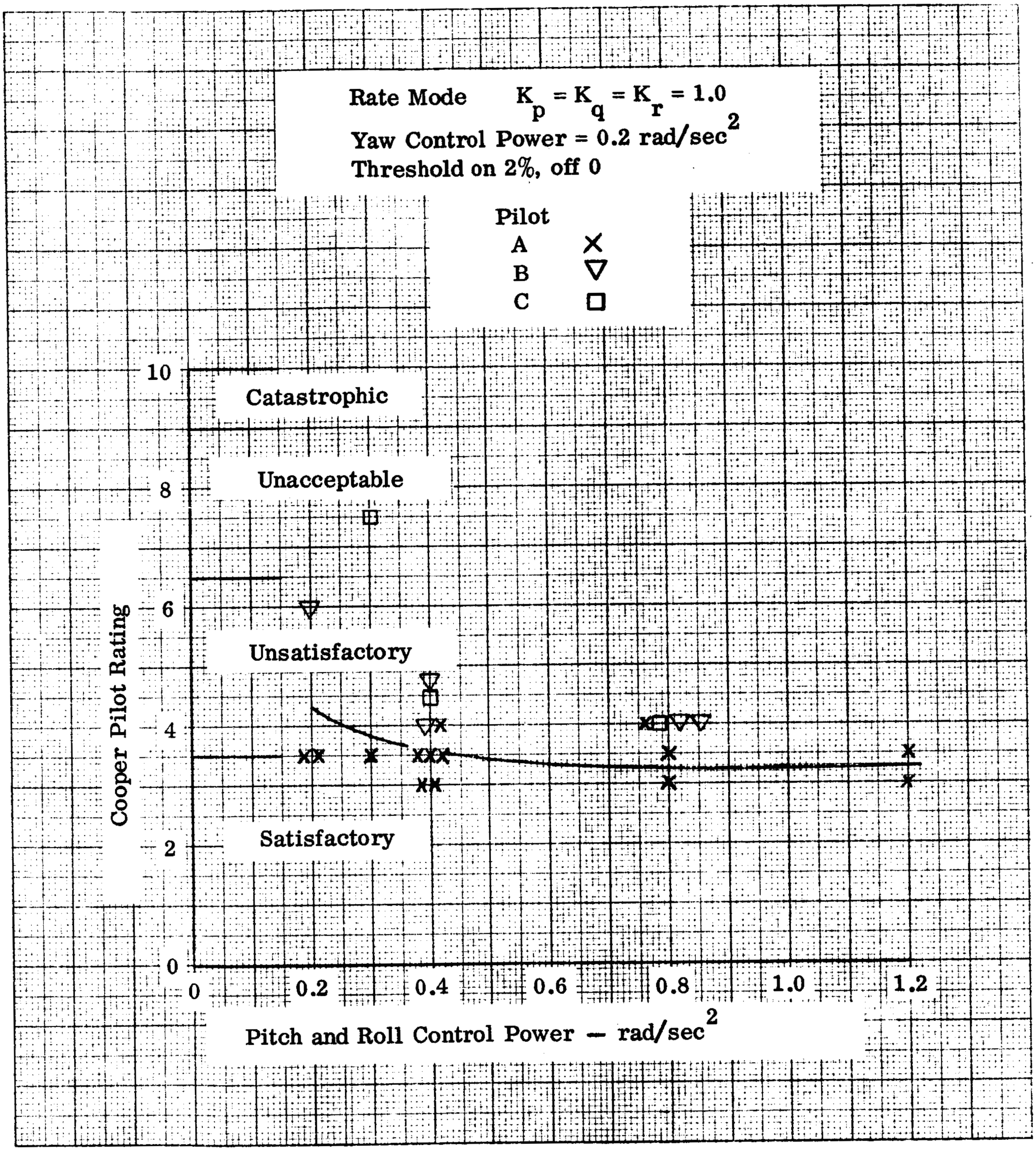


Figure 3-7. Pilot Rating - Descent Mission - Simulation Mode

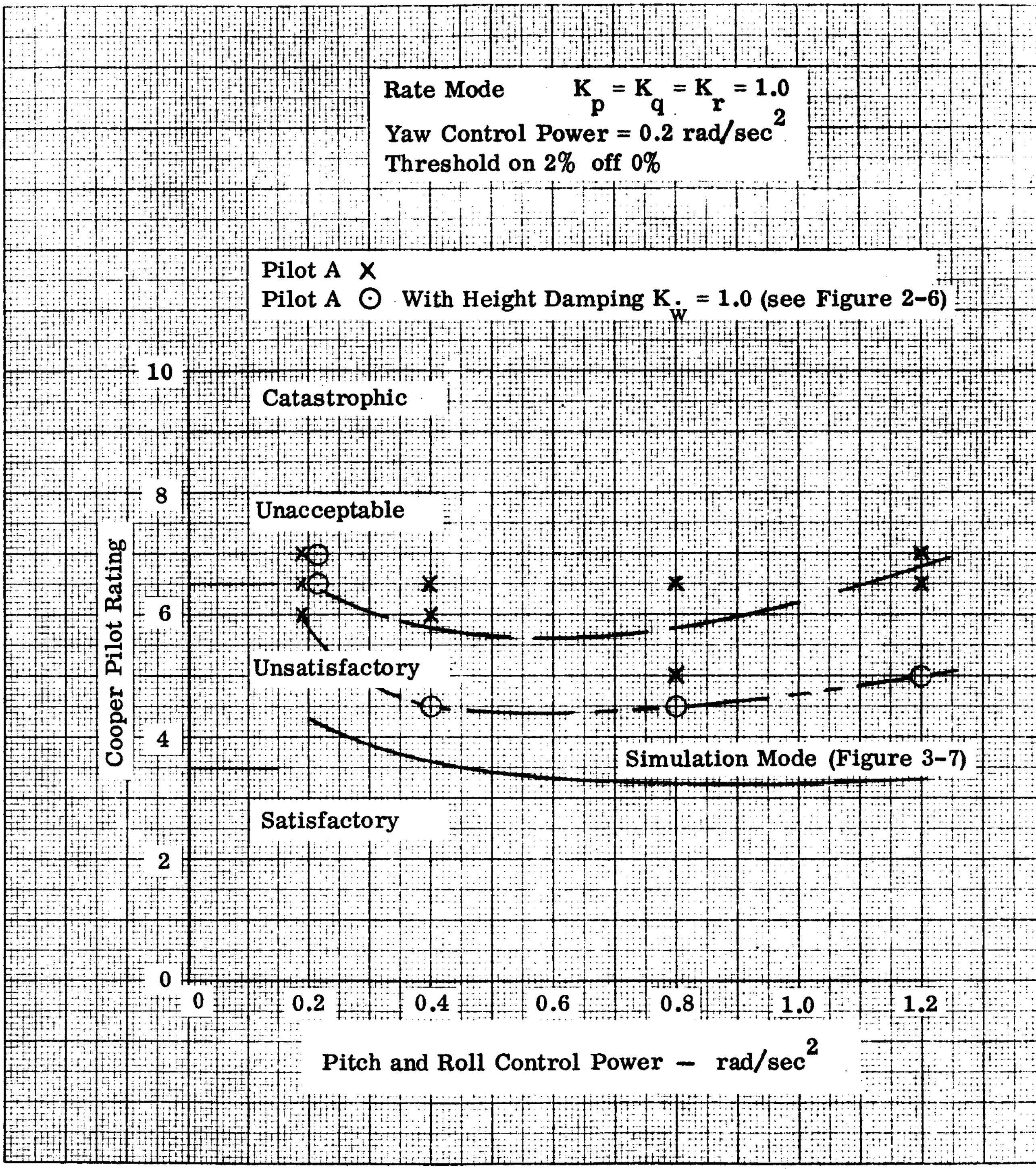


Figure 3-8. Pilot Rating - Descent Mission - Engine Centered Mode

thrust being rotated as is the case in the simulation mode. This difficulty in controlling translation showed up particularly during the touchdown phase of the mission.

3.7.1.3. Effect of On-Off Threshold. - If the size of the on-off threshold is increased above two percent stick travel, the pilot ratings of control show a marked deterioration. Thresholds smaller than two percent do not show a significant improvement when rate feedback gain is 1.0, but when rate feedback gain is reduced (i.e., stick sensitivity increased) smaller thresholds can be beneficial. This is probably due to the pilot's preference for small control deflections and the method of control.

It was noted that each of the three pilots developed a technique of attitude control not by clasping the hand rest at the top of the stick and thus having to move his whole arm when making control deflections, but rather, by holding the stick in the fingers, as one would a pencil, low enough for the pilot's arm to rest on his leg. In this manner, stick movements could be made using the fingers with occasional wrist movement. This immediately suggests the use of a side arm controller combined with a suitable arm rest instead of the central stick. Either a pencil type or fingertip (button type) could be used.

The above comments refer to the rate command mode. Here, to maintain an attitude against moments, the stick has to be constantly "pumped" so as to get short bursts of thrust from the attitude rockets. In the attitude position command mode the stick has to be held deflected to maintain any attitude other than the neutral position. Hence if an attitude mode is likely to be the most widely used then the conventional center stick would be the better choice (e.g. as in conventional airplane).

3.7.1.4. Effect of Attitude Rate Damping. - The rate feedback gains K_p, K_q, K_r define the stick sensitivity. With the simulator setup full stick or pedal deflection corresponds to $\frac{1.0}{K_p, K_q \text{ or } K_r}$ rad/sec. Figure 3-9 shows the effect of this parameter on the pilot ratings for both engine centered and lunar simulation modes. When $K_p = K_q = K_r = 0$ we have no rate damping; this is the acceleration command mode. As Figure 3-9 indicates, it was not found possible to fly in the acceleration mode. It will be noted that the optimum level of damping occurs at a higher value (lower stick sensitivity) in the engine centered mode than the lunar simulation mode. Also, with the optimum damping, the rating for the engine centered mode approaches the acceptable region. The reason for this improvement in rating with increased

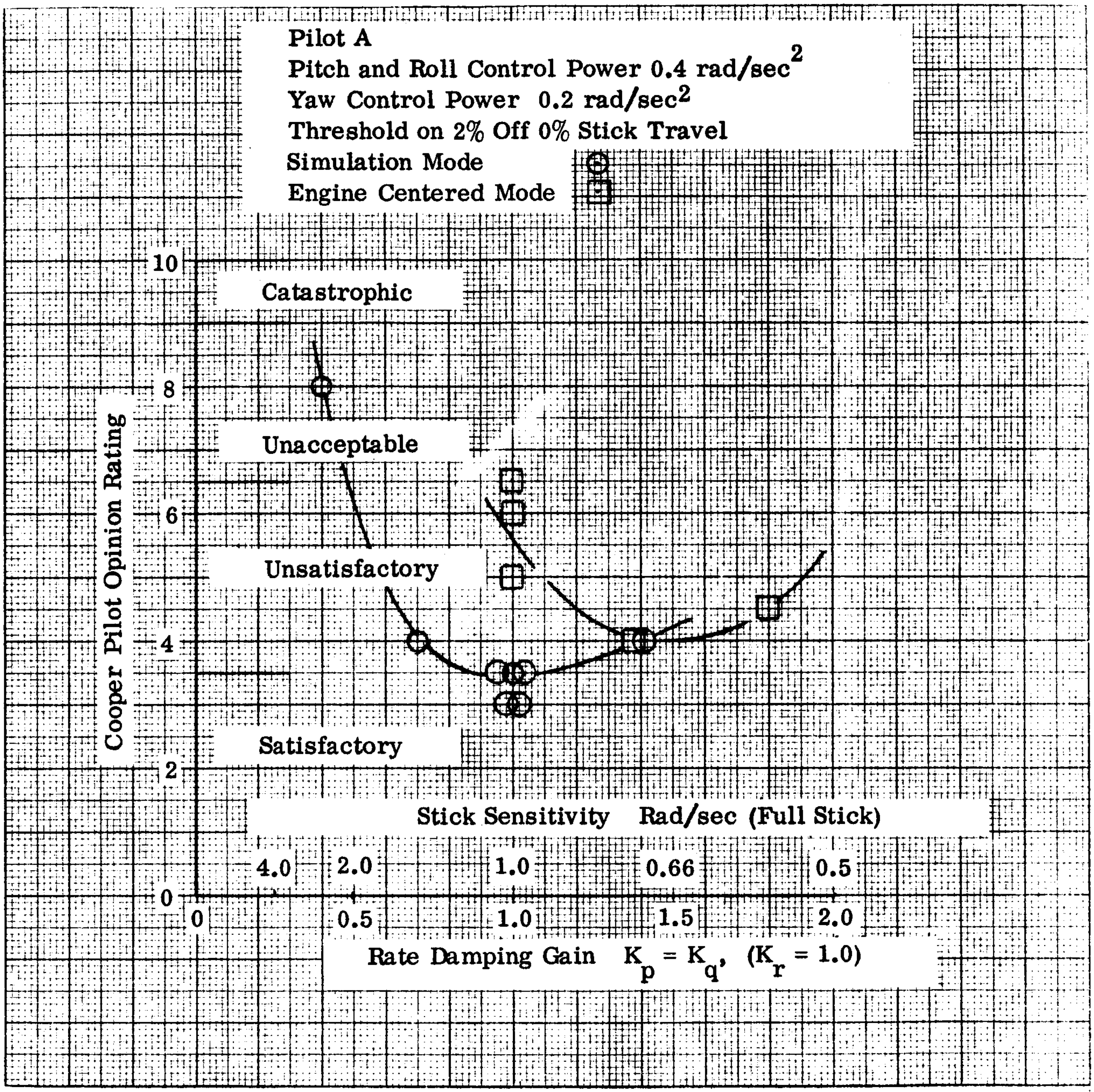


Figure 3-9. Effect of Stick Sensitivity (Rate Damping) - Descent Mission

rate gain may be because the pilot prefers the less sensitive control to help compensate for the high translational accelerations which occur when the engine is centered.

3.7.1.5. Attitude Position Command Mode. - A series of flights in this mode with $K_\phi = K_\theta = K_\psi = 1$, K_p, K_q, $K_r = 0.5$, and thresholds of on two percent off zero stick travel showed that:

(1) Attitude control is a very simple task for the pilot.

(2) Fuel consumption rate is of similar magnitude to that of the rate command mode.

3.7.1.6. Increased Aerodynamic Moments. - The effect of doubling the aerodynamic moments on the engine and vehicle individually or together was to cause a deterioration of about 1/2 pilot opinion rating at a control power level of 0.4. Tests at lower control power were not carried out, but it is to be expected that the lowest acceptable level of control would increase from the 0.2 to 0.3 range to the 0.3 to 0.4 range. There was a proportional increase of fuel consumption with the increased aerodynamic moments. It should be noted that, due to its symmetry, there are no aerodynamic yawing moments on the simulated vehicle outer frame. However, the LLRV configuration does have unstable yawing moments and these may cause a further deterioration of the attitude control pilot ratings.

3.7.2. Height Control. - Throughout the tests, the pilots rated height control as follows:

	RATING	
PILOT	ENGINE CENTERED MODE	LUNAR SIMULATION MODE
A	6	4.5
B	6.5	6
C	5	5

For the lunar simulation mode, these ratings would be unsatisfactory and for the engine centered mode on the border, unsatisfactory - unacceptable. It should be noted that these ratings must be considered as the overall values for the vehicle.

The main criticism of height control was that the throttle types are mixed, so that a pulling motion of the jet engine throttle reduces thrust and pulling the lift rocket lever increases thrust. The pilots found this confusing even though a single simulator run involved the use of either one or the other control, not both. In the real vehicle, where the pilot will change in flight from engine centered mode to lunar simulation mode and hence from lift rocket control to jet engine control, the throttle configuration is likely to cause even more confusion. Apart from this criticism, height is inherently difficult to control because of the effective lift change whenever the pitch or roll attitude varies. Considerable practice was required by the pilots before the landing mission could be flown accurately. This amounted to one to two hours practicing the descents in addition to the previously accrued 10 hours of simulator time performing the preliminary mission.

3.7.2.1. Interchanging Throttles. - In response to the criticisms regarding the conflicting throttle types cited, the lift rockets were set up to be controlled by the conventional throttle quadrant instead of the collective pitch type lever. This setup was preferred by the pilots, although further work would be required to optimize the throttle sensitivity (i.e., inches/g.).

3.7.2.2. Height Damping. - Introduction of height damping in the engine centered mode produced a favorable increase in the pilot opinion ratings of between 1/2 and 1.0 points, depending on the attitude control power (see Figure 3-8). As would be expected, the minimum flyable control power remained the same with height damping as without.

3.7.3. Fuel Consumption. -

3.7.3.1. Attitude Rockets. - The fuel consumption data from the preliminary mission studies (Figure 3-10) exhibits considerable variation from pilot to pilot. The only trend is to suggest an increase in rate of fuel consumption at the greater control power levels. Data from the descent missions (Figure 3-11) show much better agreement except for pilot C. The divergence in data from pilot C is probably due to his shorter simulator time.

It seems reasonable to assume that for a similar mission, a sufficiently trained pilot could achieve a rate of fuel consumption with the basic configuration (threshold +2% -0%, $K_p = K_q = K_r = 1$) of from 12 to 17 lb/min in the lunar simulation mode and from 14 to 19 lb/min in the engine centered mode.

Changing the threshold and rate feedback gain (stick sensitivity) had an effect on the rate of fuel consumption, that was similar to the effect on the pilot opinion rating (see Figure 3-12).

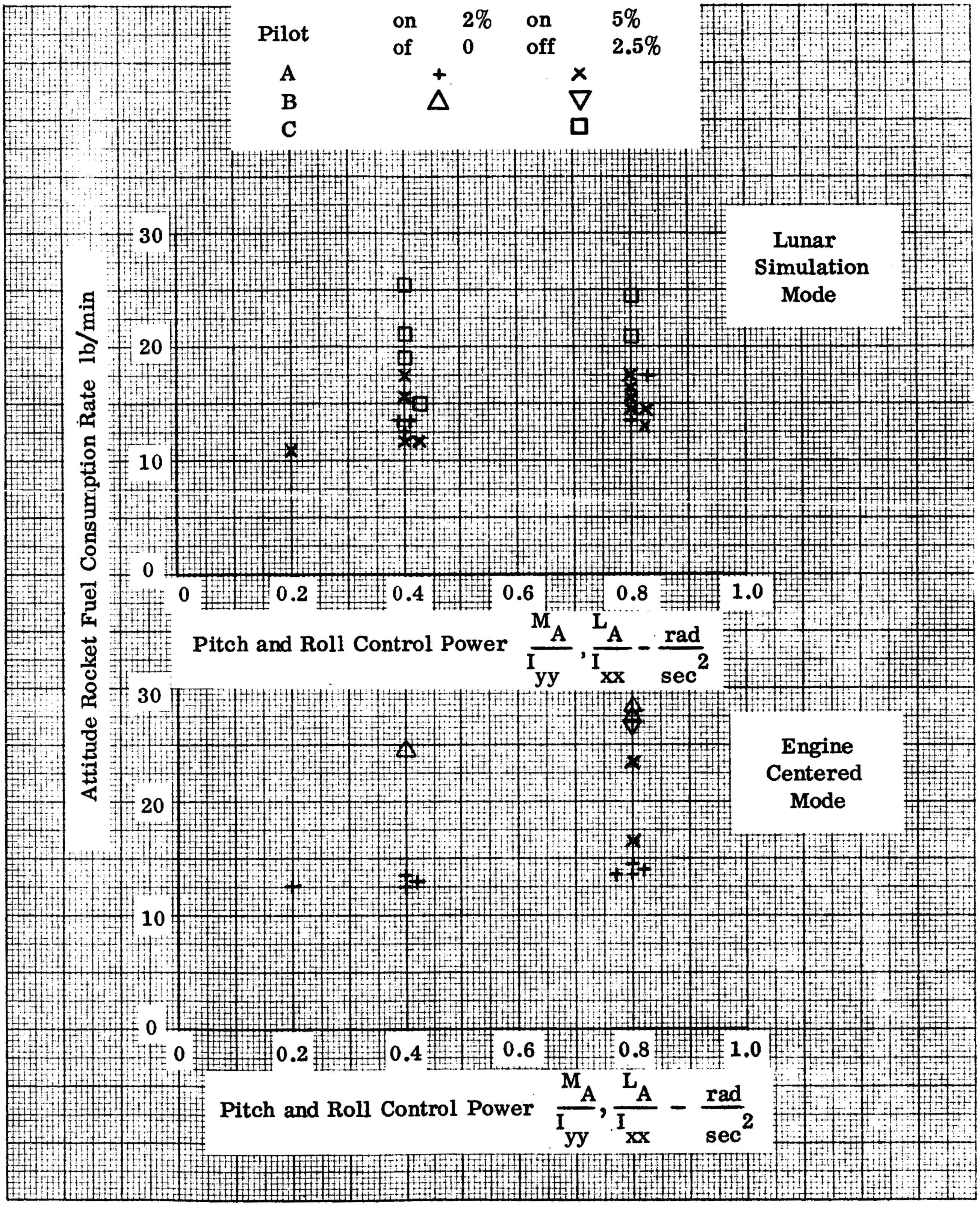


Figure 3-10. Attitude Rocket Fuel Consumption Rate - Preliminary Mission

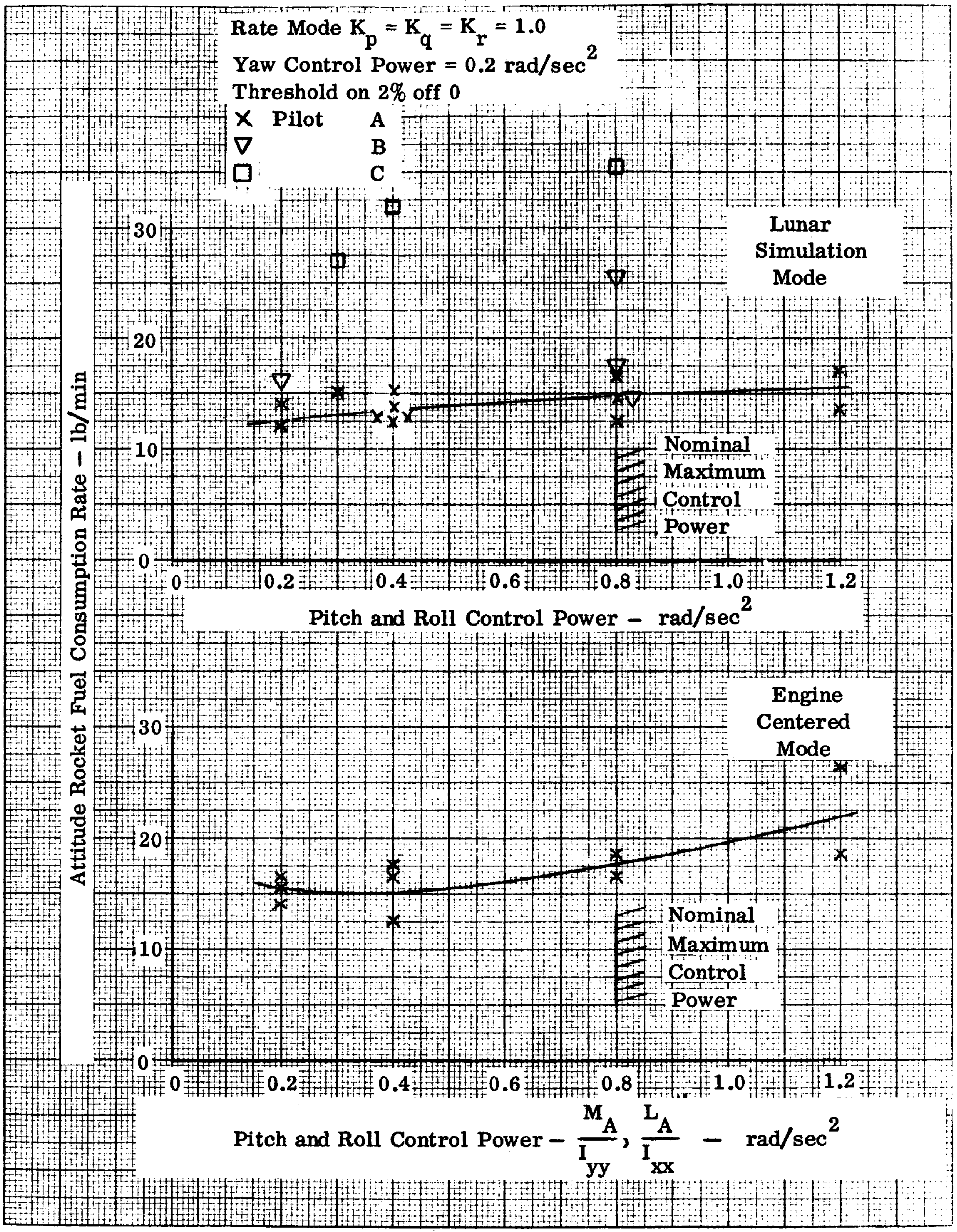


Figure 3-11. Attitude Rocket Fuel Consumption Rate - Descent Mission

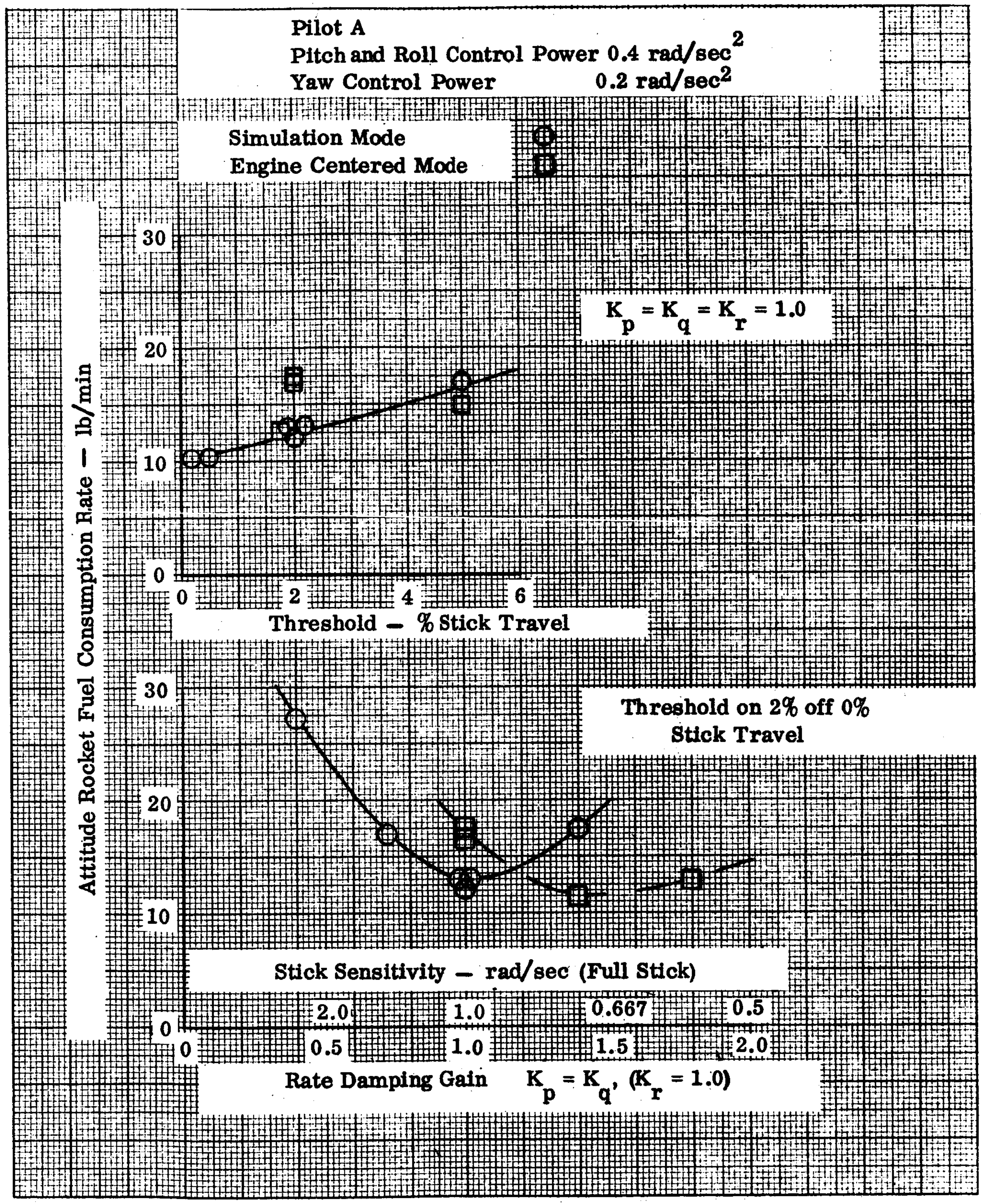


Figure 3-12. Attitude Rocket Fuel Consumption Rate Effect of Threshold and Stick Sensitivity - Descent Mission

Decreasing thresholds from on at two percent, off zero to on at 0.5 percent off zero reduced the fuel consumption rate from about 12.5 lb/min to 10 lb/min for the lunar simulation mode. Insufficient data was obtained to define the effect in the engine centered mode.

Changing the rate feedback gain when in the lunar simulation mode caused an increase in rate of fuel consumption from about 13 lb/min at $K_p = K_q = K_r = 1.0$ to 19.5 lb/min at $K_p = K_q = 0.6$, $K_r = 1.0$ and 17.5 lb/min at $K_p = K_q = 1.4$, $K_r = 1.0$. In the engine centered mode, the minimum fuel consumption rate occurs at approximately $K_p = K_q = 1.5$, $K_r = 1.0$, being 11 lb/min. At $K_p = K_q = K_r = 1.0$, fuel consumption rate is 17 lb/min.

Flights in the position command mode indicated that the fuel consumption rate was of the order 10-13 lb/min. This is of similar magnitude to the minimum values achieved by the pilot in the rate mode.

3.7.3.2. Lift Rockets. - The fuel used by the lift rockets is almost directly proportional to the time they are fired. This has been plotted on Figure 3-13 for the lunar simulation mode descents. It can be seen that fuel used ranges from 320 lb to 530 lb for the descent from 1,000 ft while translating forward 1,000 ft.

The pilots were asked to complete these descent missions in as short a time as possible. The actual time taken is shown in Figure 3-14 to be between 1.5 and 2.0 minutes for both the lunar simulation and engine centered modes. Since the mission should only take about 70 seconds (1,000 ft at 20 ft/sec plus about 10 seconds for acceleration and 10 seconds for deceleration), these times suggest that the order of 0.5 minute should be added to mission time estimations to allow for the actual positioning - hover - touchdown phase.

3.7.3.3. Fuel Used for Takeoff and Climb. - A series of takeoff and climb missions, during which the pilot endeavored to use a minimum of attitude control fuel, showed that a minimum of around 10 lb/min could be expected in the rate command mode.

3.7.4. Recovery Procedure in Case of Jet Engine Failure. - If a jet engine failure occurs before the lunar simulation phase of the flight has been commenced, there will be approximately 500 pounds of lift rocket fuel for the emergency rockets. Figure 3-4 illustrates the recovery profiles which could be used if the weight at beginning of recovery is 3400 pounds.

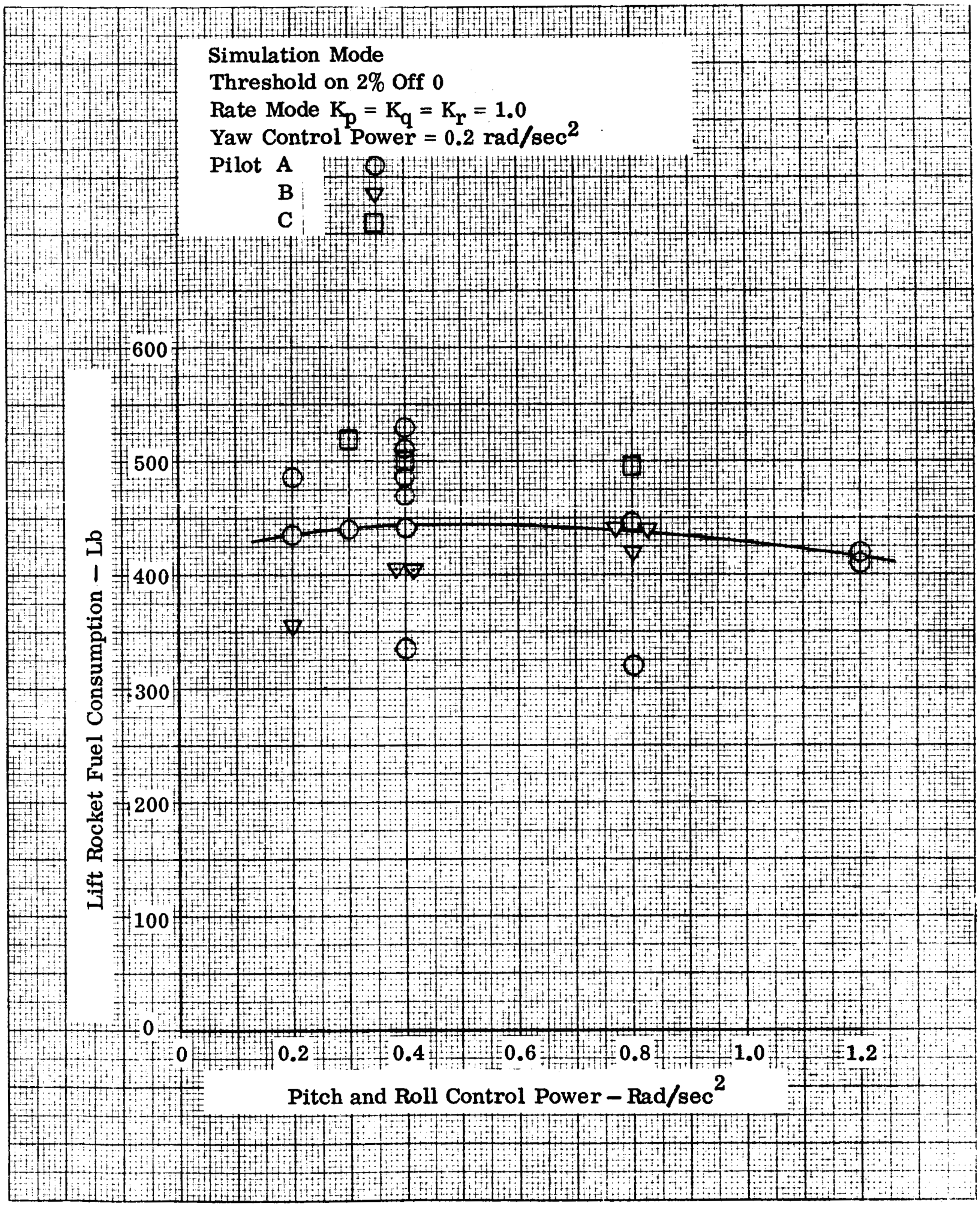


Figure 3-13. Lift Rocket Fuel Consumed During Descent Mission

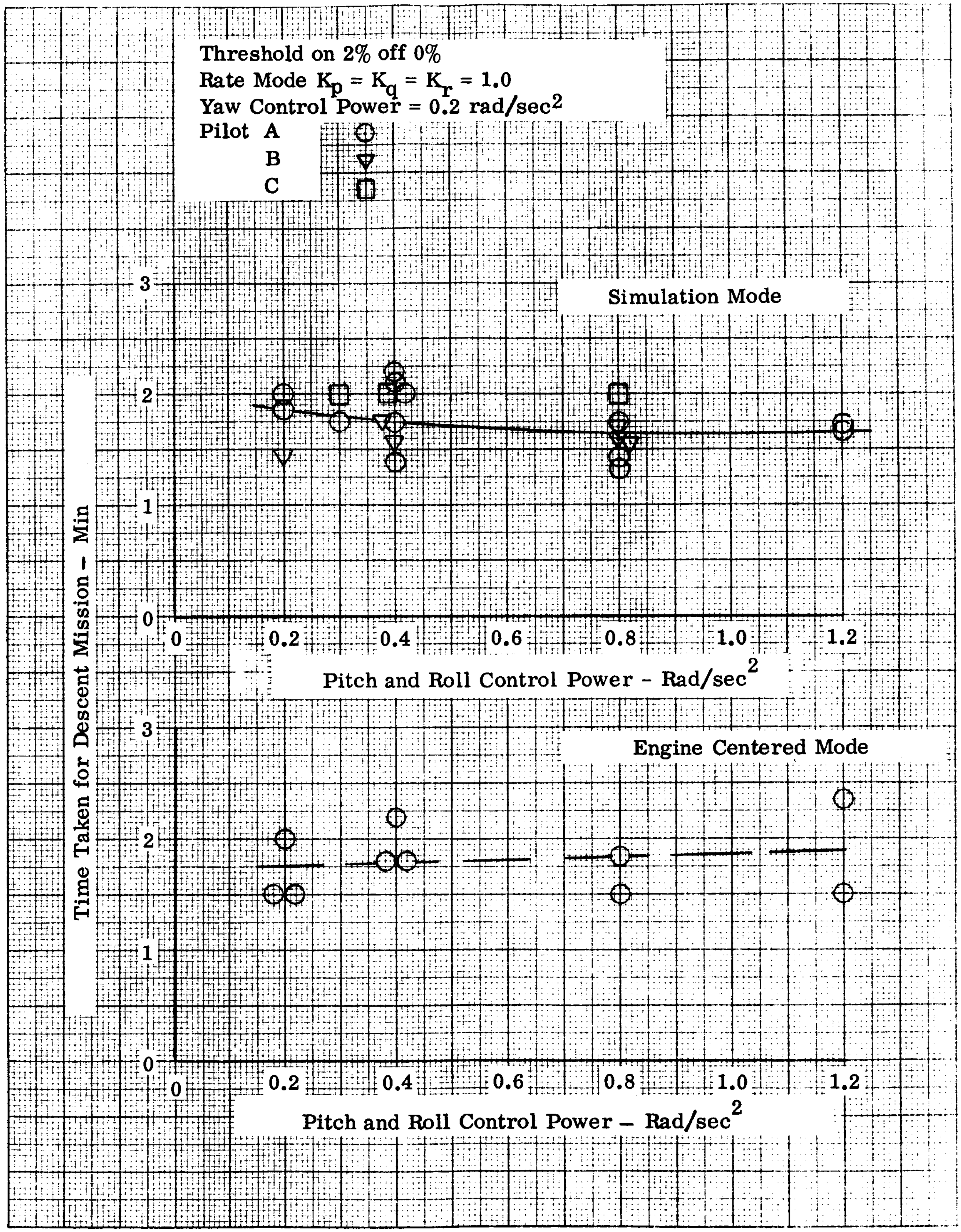


Figure 3-14. Time Taken for Descent Mission

Assuming failure occurs in the "free fall region", the emergency parachute must be deployed and the vehicle allowed to free fall until the descent velocity takes the vehicle past the "lift rocket fuel boundary". A series of actions are now open to the pilot, the boundaries being defined by the following two cases:

(1) Continue the free fall so that the terminal descent velocity of 100 ft/sec is achieved. When the altitude reaches the thrust limited boundary (350 feet for the weight being considered), apply full emergency rocket thrust and the vehicle will decelerate and touch down at 10 ft/sec. Sufficient fuel is available for a 10 ft/sec descent from 100 feet should the lift rockets have been applied at 450 feet instead of 350 feet.

(2) As the vehicle passes through the lift rocket fuel boundary, apply the emergency rockets to give a thrust equal to the weight and hence maintain a constant rate of descent down to the thrust limit boundary, (44 ft/sec and 150 feet, respectively, for this case). At this altitude apply full emergency rocket thrust and the vehicle will decelerate to reach the ground at 10 ft/sec. This form of descent uses all the available lift rocket fuel. It should be noted that excursions into lower descent velocities (less than 44 ft/sec in this case) will use all the fuel before touchdown.

In the simulator program, only case (1) was investigated by the pilots. It was found that the vehicle attitude was controllable at the maximum descent rate of 100 ft/sec if the control power was satisfactory for level flight.

Application of full thrust at the precise height was found extremely difficult. If thrust was applied too early there was a distinct tendency for the vehicle descent velocity to reach zero and begin climbing again. If thrust was applied too late, the velocity of impact was too great.

This form of recovery was considered decidedly hazardous. A profile approaching case (2) would be more desirable, since the maximum descent rate is halved and hence twice as much time is available for the pilot to initiate emergency rocket thrust. It will be realized however, that both the "lift rocket fuel boundary" and the "thrust limited boundary" are functions of vehicle weight at the start of emergency descent. Thus, to perform a descent case (2), the pilot would need to know his position relative to both of these changing boundaries. With case (1), emergency descents from greater than about 900 feet require knowledge of only the thrust limited boundary at 100 ft/sec. Descents from less than 900 feet will have a free fall curve which intersects the thrust limit boundary at less than the chute terminal velocity, so the pilot needs to know his position relative to the boundary.

For altitudes up to 1300 feet and weights less than 3400 pounds, the procedure could be standardized by the following technique:

DEPLOY PARACHUTE

FREE FALL UNTIL EITHER

RATE OF DESCENT = 54 FT/SEC OR ALTITUDE = 180 FT

MAINTAIN RATE OF DESCENT
AT 54 FT/SEC TO 180 FT

APPLY FULL THRUST AND DECELERATE TO 10 FT/SEC

MAINTAIN 10 FT/SEC DESCENT RATE TILL TOUCHDOWN

For a failure above 1300 feet altitude, the pilot would have to use the "thrust limited boundary" by free-falling to 350 feet and applying full thrust. These boundaries are for reference only and apply to the thrust and initial weight values of 3600 pounds and 3400 pounds, respectively.

SECTION IV

ESTIMATED HANDLING QUALITIES

The following discussions of estimated handling qualities are based on the results of the piloted analog simulator study, Section III, and on comparisons of the aerodynamic characteristics of the simulated vehicle and the actual LLRV. The simulated vehicle was essentially representative of the actual vehicle except for the aerodynamic forces and moments.

Figures 2-7 through 2-10 show the relative values of drag and moments in the engine centered mode for the LLRV and the simulated configuration. As can be seen, the drag of the LLRV is of similar magnitude to that simulated, so the vehicle and engine tilt angles will be similar to those simulated for a given translation rate.

Pitching moments are of similar magnitude but of opposite sign, being nose up on the LLRV but largely nose down on the simulated vehicle. In both cases, the magnitude is sufficient to produce ± 0.2 rad/sec^2 acceleration in the range of 40 to 60 ft/sec. It is possible that the nose-up moments, which are speed stable, would result in a favorable effect on the handling qualities of the LLRV compared with the simulator.

Rolling moments on the LLRV are of opposite sign to those simulated and are also of larger magnitude. At 60 ft/sec, $\beta = 20$ degrees, the rolling moments are equivalent to about:

-0.264 rad/sec^2 for the LLRV and

$+0.0290$ rad/sec^2 for the simulated vehicle.

When sideslipping this is likely to cause a significant deterioration of the control rating of the LLRV.

Due to the symmetry of the simulated vehicle, the yawing moments were zero in the engine centered mode and small when in the lunar simulation mode. On the LLRV there are yawing moments in both modes. In the engine centered mode the yawing moments are equivalent to about -0.048 rad/sec^2 at 60 ft/sec and $\beta = 20$ degrees. This fact, coupled with the large rolling acceleration, will probably result in a marked deterioration of handling qualities from those achieved on the simulator.

In view of the foregoing comments, the handling qualities data of Paragraph 3.7 should be considered as illustrating the effects of the various parameters rather than as absolute pilot opinion ratings for the vehicle.

The following is a discussion of the dominant parameters and their effects on attitude control, height control, and fuel consumption.

4.1. ATTITUDE CONTROL.

4.1.1. Attitude Acceleration Command Mode. - It was found impossible to fly the simulator with this mode of control. However, with the added motion and visual cues it may be possible to fly the actual vehicle in this mode when the pilots have had considerable experience and/or flight experience in other modes.

4.1.2. Attitude Rate Command Mode. - This mode was found to be flyable with the basic parameters set at a variety of values. A discussion of these is given in the following paragraphs.

4.1.2.1. Control Power. - The simulator study indicated that for descent missions, the pitch and roll control power had little effect provided it was above the minimum of around 0.2 to 0.3 rad/sec^2. This minimum requirement for control power is dependent on the maximum velocities u, v, and w which will be encountered during the mission. The speeds at which the aerodynamic moments equal rocket moments that would give a control power of 0.2 rad/sec^2 are indicated in Figures 2-8, 2-9, and 2-10 for the engine centered mode. These boundaries are not the actual speed limits because, in fact, a margin of control power would be required to allow for stabilizing the vehicle even if the aerodynamic moments were zero. It should be noted that the unstable yawing moments will induce sideslip and hence rolling moments. A margin will therefore have to be allowed to compensate the effective halving of control power when overcoming both pitching and rolling moments.

4.1.2.2. Rate Feedback Gains (Stick Sensitivity). - The simulator was set up so that a rate feedback gain of 1.0 corresponded to a stick and pedal sensitivity of 1.0 radian/second for full stick travel. Figure 3-9 shows the effect on pilot opinion rating of varying the stick sensitivity both for the engine centered and the lunar simulation modes. Yaw pedal sensitivity was maintained at 1.0 rad/sec. The optimum pitch and roll sensitivity was found to be about 1.0 rad/sec in the stabilization mode and 0.6 rad/sec in the engine centered mode.

4.1.2.3. Rocket On-Off Threshold. - Figure 2-4 shows that the attitude control rocket control logic incorporated on the LLRV results in an effective threshold at 45 degrees to the one simulated. This means that, when there is a large error in the pitch channel, the pilot will have to move a greater distance (in roll direction) before the roll rockets fire than if the pitch error will near zero. Similarly, if a large roll error signal exists (roll rate or roll attitude not near commanded valves), a large stick deflection in the fore or aft direction would be required to fire the pitch rockets. A similar situation existed in the simulated vehicle, but there the large stick motions required were in the diagonal (combined pitch/ roll) direction. It is impossible to say how much effect this difference between the actual LLRV and the simulated vehicle will have on the pilot's opinion of the handling qualities. However, if rates of stick deflections are kept small so that the vehicle can keep up with the commands, large error signals will not occur and the difference should not be noticeable.

The simulator study showed that the pilot opinion rating improves with decreasing on-off threshold (Figure 4-1). However the improvement with thresholds below one percent of stick travel (or 0.57 deg/sec rate error) is not significant enough to outweigh the detrimental effects of the increased rate of rocket pulsing. It should be noted that the rocket duty cycle tests during development were based on the assumption that the rocket pulse rates will not exceed two pulses/second. Pulse rates above this are considered undesirable due to possible excessive valve wear. On-off thresholds less than one percent are therefore not recommended.

4.1.2.4. Attitude Position Command Mode. - This mode was found very easy to fly. It was therefore not investigated in detail during the simulated flights.

4.2. HEIGHT CONTROL.

Height control was found to be a difficult task. The comments of Paragraph 3.7.2 apply to the vehicle as well as the simulator, although the added motion and visual cues sensed by the pilot when flying the vehicle should make the task slightly less difficult. It may be found advantageous for the pilot to practice height control in the vehicle using the attitude position command system, thus minimizing the attitude control task until he becomes proficient at height control. Depending on the available thrust to weight ratio, the descent velocity is limited by the height required to decelerate to zero velocity before reaching the ground. These boundaries are given on Figure 4-2 for various weights.

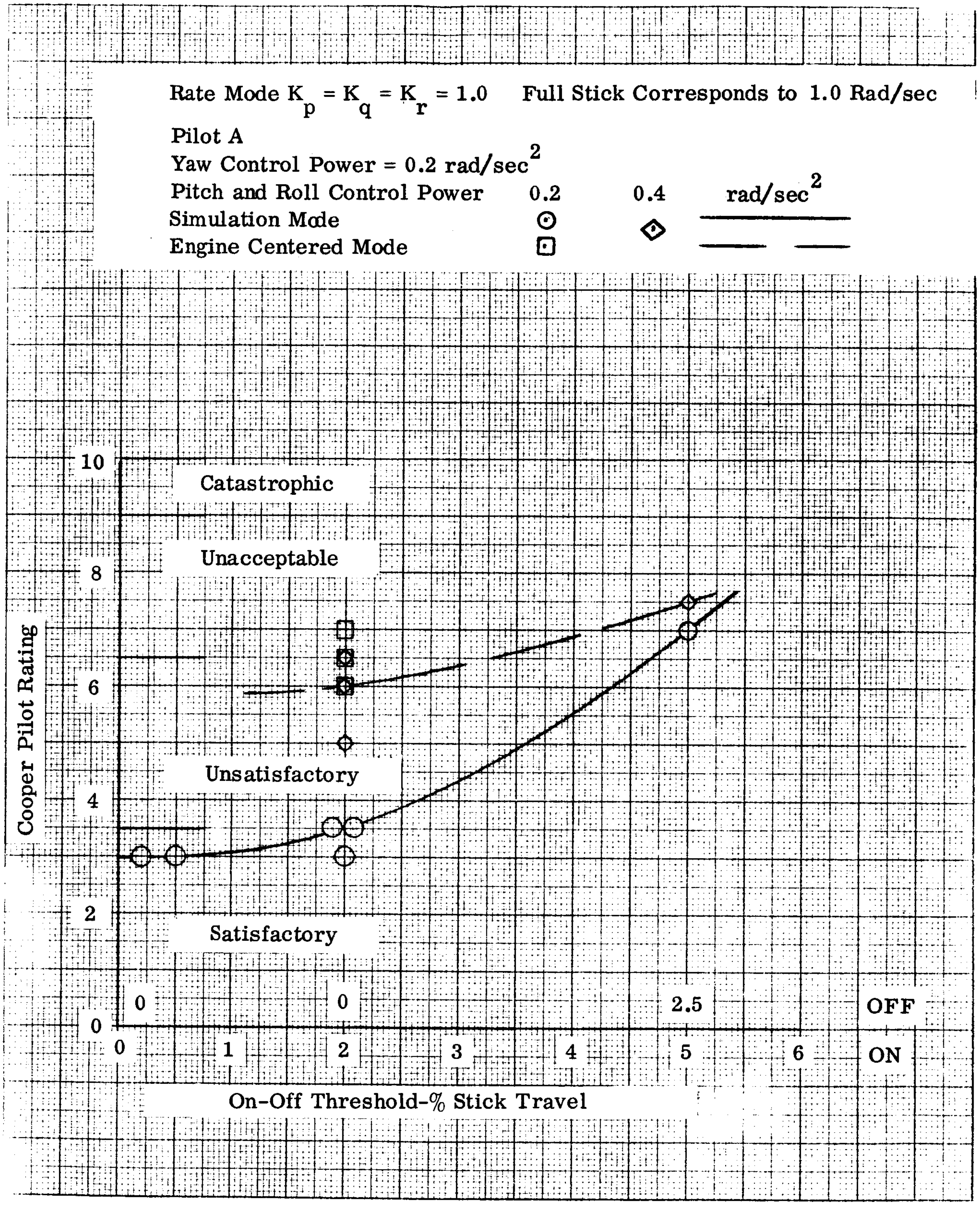


Figure 4-1. Effect of On-Off Threshold - Descent Mission

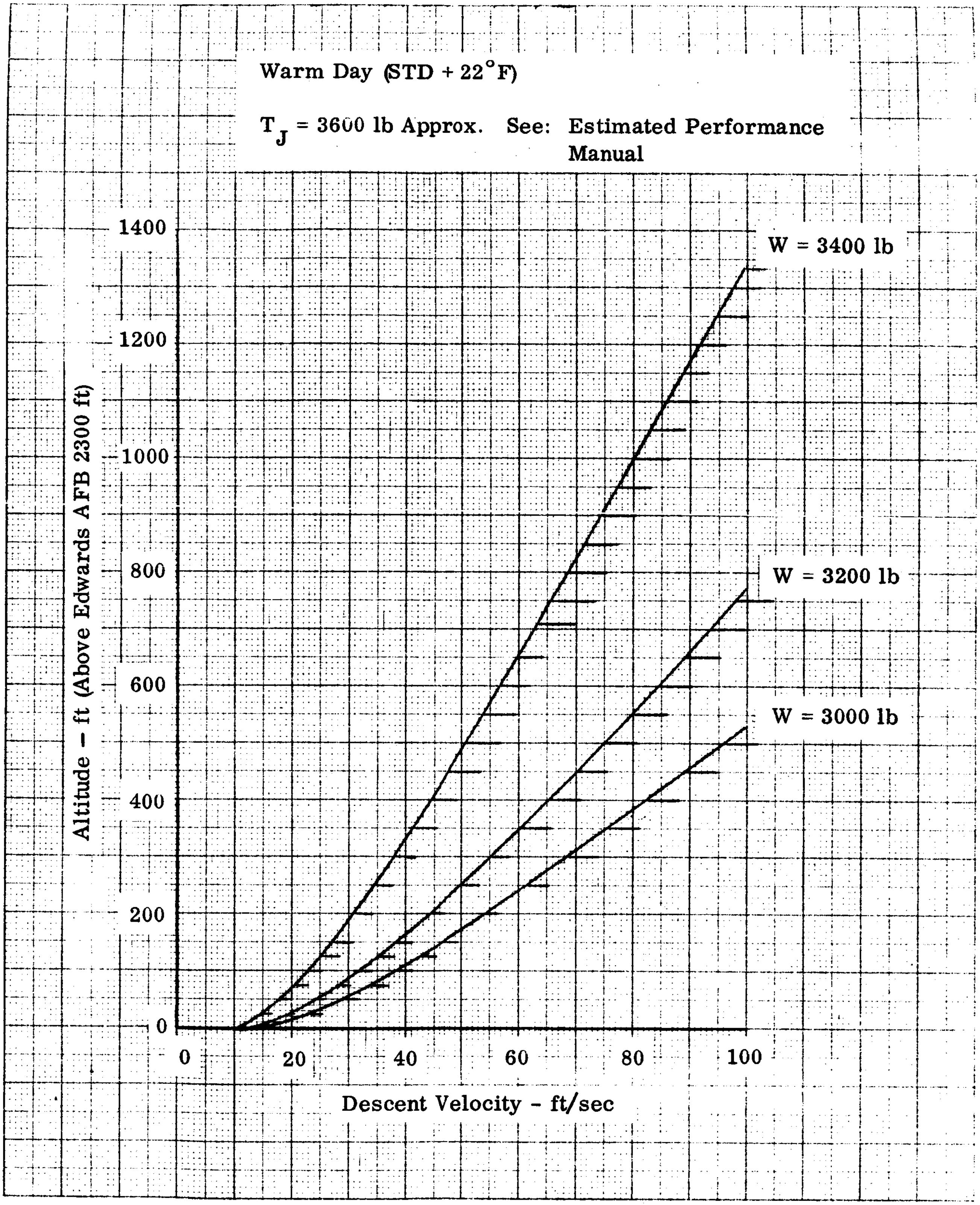


Figure 4-2. Jet Thrust Limited Descent Velocity Boundaries - Engine Centered Mode

4.3. FUEL CONSUMPTION.

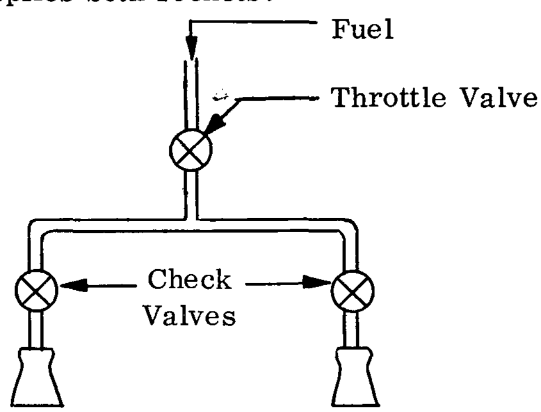
Attitude rocket fuel consumption rate was found to vary considerably from pilot to pilot and with the individual pilot's experience. Results from the simulator study (Section III) suggest that attitude control rocket fuel consumption for a trained pilot will be in the range 11 to 17 lb/min in the stabilization mode or engine centered mode. However, the ratios of moment arm to inertia on the LLRV are about 75 percent of those simulated. This may mean that the higher level of rocket thrust required for a given control power will result in a 25 percent increase in fuel consumption rate.

Lift rocket and jet engine fuel consumption rates were almost exactly equal to the product of the nominal thrust setting and the specific fuel consumption. These can be determined from the flight plan and the estimated performance handbook.

4.4. EMERGENCY RECOVERY PROCEDURES.

4.4.1. Jet Engine Failure. - This has been discussed in detail in Paragraph 3.7.4. The boundaries presented in that section should be treated as reference only as they may change when the latest LLRV configuration weight, drag, engine thrust, etc. are incorporated.

4.4.2. Lift Rocket Engine Failure. - The layout of the lift rocket fuel supply is as indicated: i.e., a common control valve supplies both rockets.



In view of this arrangements the possible malfunctions are:

Increasing Thrust:

(1) both fail to fire.
(2) one fails to fire.
(3) thrust increment one side greater than the other.

Decreasing Thrust:

(4) one rocket suddenly cuts out.

(1) If both fail to fire - pilot abandons the lunar simulation phase of the flight and lands using the jet engine.

(2) If one fails to fire - full thrust produces a rolling moment of approximately 1415 lb ft.

$$\frac{L}{I_{xx}} = 1.29 \text{ rad/sec}^2$$

Maximum roll control = 0.981 rad/sec^2

Minimum roll control = 0.098 rad/sec^2

Out of balance rolling moment = 0.309 (minimum)
= 1.192 (maximum)

Hence pilot will roll through about 60 degrees in 10 seconds at best
and 60 degrees in 1.75 seconds at worst

Clearly this would be catastrophic so when initiating the lunar simulation mode, the pilot must apply thrust gradually enough to be able to recognize an asymmetric condition and reduce thrust before it becomes uncontrollable.

(3) Out of balance thrust - reduce thrust level to give controllable conditions.

(4) One rocket cuts out - same comments as (2) apply. However, since this may occur at some stage in the flight when the pilot is not operating the lift rocket throttle, it would probably take the pilot longer to recognize the condition and reduce rocket thrust. Clearly practice on the simulator is required to attain maximum proficiency.